A Transactive Energy Management Framework for Regional Network of Microgrids

Daneshvar, Mohammadreza ; Mohammadi-Ivatloo, Behnam ; Asadi, Somayeh ; Abapour, Mehdi; Anvari-Moghaddam, Amjad

Published in:
SEST 2019 - 2nd International Conference on Smart Energy Systems and Technologies

DOI (link to publication from Publisher):
10.1109/SEST.2019.8849075

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

A Transactive Energy Management Framework for Regional Network of Microgrids

Mohammadreza Daneshvar
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
m.r.daneshvar@ieee.org

Behnam Mohammadi-ivatloo
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
bmohammadi@tabrizu.ac.ir

Somayeh Asadi
Department of Architectural Engineering
Pennsylvania State University
Pennsylvania, USA
asadi@engr.psu.edu

Mehdi Abapour
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran
abapour@tabrizu.ac.ir

Amjad Anvari-Moghaddam
Department of Energy Technology
Aalborg University
Aalborg, Denmark
aam@et.aau.dk

***Abstract*—To maximize the microgrids profit in presence of renewable energy resources (RERs), this paper employs the transactive energy (TE) technique for optimal scheduling of the distributed energy resources (DERs) throughout the system. Microgrids can exchange energy with the main grid not only to meet their demand but also to make a profit by active participation in energy and reserve provision process. In this regard, TE can be applied as an effective solution for energy supply management and dynamic balancing between the microgrids and the power grid. In this paper, the participation of five grid-connected commercial microgrids in day-ahead (DA) market is considered. The applicability and the satisfactory performance of the proposed approach are tested and validated on a 10-bus IEEE test system. Simulation results indicate that maximum profit can be achieved for the microgrids with optimal scheduling of the DERs based on the TE approach.**

Keywords—transactive energy, microgrid, renewable energy resources, day-ahead market

NOMENCLATURE

Indices	
t	Index of scheduling time periods.
i	Index of microgrids.
k,j	Index of buses.
s	Index of scenarios.
Parameters	
M	Number of microgrids connected to the examined distribution network.
N, T	Number of buses and scheduling hours.
$P_{j,t}^{D}$	Total electrical demand.
$\rho_{t,s}^{DA}$	Day-ahead (DA) market price.
$\rho_{t,s}^{R+}, \rho_{t,s}^{R-}$	Regulation prices for selling energy to (down-regulation) or purchasing needed energy from (up-regulation) the real-time (RT) balancing market.
σ^{-}, σ^{+}	Relative differences between regulation prices and DA market price.
$\mathrm{Pr}ob_{s}$	Probability of scenario *s*.
Δt	Time interval for scheduling problem.
NS	Number of generated scenario for the uncertainty parameter.
$\rho_{t,s}^{Sell}$	Selling electricity price to the consumers.
$Csu_{i,t,s}^{DG}, Csd_{i,t,s}^{DG}$	Cost of the DGs stat up and shut down.
$\alpha_{j}^{IL}, \beta_{j}^{IL}$	Cost coefficients of IL.
$\alpha_{i}^{DG}, \beta_{i}^{DG}, \gamma_{i}^{DG}$	Cost coefficients of DG unit.
ω_{i}^{BESS}	Cost coefficient of BESS related to the life time degradation of BESS.
η_{L}^{BESS}	Leakage loss factor of BESS.
ICB, LCN	Investment cost and life cycle number of BESS.
E_{R}^{BESS}	Rated energy capacity of BESS.
$R_{j,l}, Y_{j,l}$	Resistance and admittance of feeder *l-j*.
$P_{i,t,s}^{W,up}$	Upper limit of wind turbine active power.
ϖ	Constant coefficient related to wind turbine modeling.
Spv_{i}, η^{PV}	Size and efficiency of PV panel.
Sr_{t}	Solar radiation at time *t*.
$P_{i,t,s}^{DG,up}, P_{i,t,s}^{DG,down}$	Upper and lower limits of DG power.
Hr_{gas}	Gas heat rate.
$R_{i}^{DG,up}, R_{i}^{DG,down}$	Ramp up (RU) and ramp down (RD) limits of the DG unit.
$MUT_{i,s}^{DG}, MDT_{i,s}^{DG}$	Minimum up and down time limits for DG units.
η_{C}^{BESS}	Charging/discharging loss factor of BESS.
$\mathrm{SOC}_{i,t}^{BESS,up}$	Maximum limit of battery SOC.
$\mathrm{SOC}_{i,t}^{BESS,down}$	Minimum limit of battery SOC.
$Pdis_{i}^{BESS,\max}$	Maximum discharging limit of BESS.
$Pchr_{i}^{BESS,\max}$	Maximum charging limit of BESS.
$E_{i,In}^{BESS}, E_{i,End}^{BESS}$	Initial and final amount of stored energy in BESS.
$P_{j,t,s}^{IL,\max}$	Maximum amount of interrupted load (IL).
$P_{j,t}^{D,\max}, P_{j,t}^{D,\min}$	Maximum and minimum power demand.
$S_{j,t,s}^{\max}$	Maximum limit of complex power.
$V_{j}^{\max}, V_{j}^{\min}$	Maximum and minimum limits of buses voltage.
$P_{exch}^{\max}, P_{exch}^{\min}$	Maximum and minimum limits of electricity exchanging with the main grid.
Variables	
$p_{t,s}^{Bid}, P_{t,s}^{Act}$	Bid/offer and actual power of microgrids.

978-1-7281-1156-8/19/$31.00 ©2019 IEEE

$\Delta P_{t,s}^{D}$	Deviation between bid/offer and actual power.
$P_{i,t,s}^{W}, Q_{i,t,s}^{W}$	Active and reactive power outputs of wind turbine.
$P_{i,t,s}^{DG}$	Active power output of DG.
$P_{i,t,s}^{PV}$	Active power output of PV panel.
$P_{i,t,s}^{BESS}$	Charging ($P_{i,t,s}^{BESS} < 0$) and discharging ($P_{i,t,s}^{BESS} > 0$) power of BESS.
$P_{i,t,s}^{IL}$	Active power output of IL.
$C_{t,s}^{D}$	Cost of deviation between bid/offer and actual power.
$C_{i,t,s}^{IL}, C_{i,t,s}^{DG}$	Costs of IL and DG.
$C_{i,t,s}^{BESS}$	Costs of BESS.
$X_{i,t,s}^{DG}$	Binary variables related to the on-off status of DG unit.
$X_{i,t,s}^{su}$	Binary variables related to the startup cost of DG unit.
$X_{i,t,s}^{sd}$	Binary variables related to the shutdown cost of DG unit.
$E_{i,t,s}^{BESS}$	Energy stored in BESS.
$V_{j,t,s}, \theta_{j,t,s}$	Voltage magnitude and angle.
$P_{i,t}^{DG,gas}$	DG gas demand.
$T_{i,t-1,s}^{DG,on}, T_{i,t-1,s}^{DG,off}$	On and off duration times (hourly) of DG units.
$\mathrm{SOC}_{i,t,s}^{BESS}$	State of charge (SOC) of BESS.
$P_{j,t,s}^{Inj}(V_t, \theta_t)$	Active power injection.
$Q_{j,t,s}^{Inj}(V_t, \theta_t)$	Reactive power injection.
$P_{j,t,s}^{Gen}, Q_{j,t,s}^{Gen}$	Active and reactive power generation in the microgrids.
$S_{j,t,s}(V_t, \theta_t)$	Complex power.

I. INTRODUCTION

A. Motivation and Background

With the advent of new energy consumers with different energy consumption behaviors, demanded energy is dynamically changing. Because of the harmful effects of conventional energy generation units such as increasing greenhouse gas emissions, microgrids as a new renewable-based energy production structure are extensively employed to meet the most of the energy demand [1]. Renewable energy resources (RERs) such as solar and wind play a vital role in clean energy generation process [2]. To provide suitable conditions for energy exchanging in smart grids, energy markets have been created with comprehensive instructions over the past few decades and RER-based microgrids participation has been promoted accordingly in such markets. In these environments, microgrids support the grid operators through different energy management and control actions while seeking their own objectives. Moreover, this support can be effectively done by optimal scheduling of the distributed energy resources (DERs) in microgrids as one of the effective and reliable ways for achieving beneficial goals.

B. Relevant Literature

Energy management issue in microgrids has attracted more attention with various goals and techniques in recent literature. For example, a multi-objective genetic algorithm has been used in [3] to optimize the fuzzy logic controller (FLC) for total microgrid profit maximization in the energy exchanging with the power grid. FLC is effectively applied to aggregate and control the energy surplus and shortage in the microgrid along with evaluating the state of a microgrid at real-time (RT). In other research, energy management is accomplished to maximize the profit of operation in the smart microgrids [4]. The authors have employed a novel method to reach the goals by considering the RT pricing (RTP). Because of the complexity of the mix integer non-linear problem in determining the day-ahead (DA) schedule of the microgrid devices in [4], the benders decomposition algorithm is applied.

In recent years, many techniques have been used for optimal energy management and control in the smart grid and all of them have some advantages and while lacking in the network analysis. In a power system, TE is introduced by the GridWise architecture council as a reliable and sustainable approach for establishing the dynamic balance between the power supply and demand. Transactive Energy (TE) is a market-based technology, which is applied in the marketplace for energy management, control, and coordination using advanced agents and protocols. Some researches in the microgrid fields have applied this technology for the assessment of various aspects of microgrids in the smart grid. For example, the multi-agent TE management system is considered in [5] to control and manage the energy demand and supply with a participant's profit maximization purpose in the system with high penetration of RERs. In [6], fog-based internet of energy architecture is employed in the TE management system to schedule DA energy consumption optimally. In addition, the inter customer energy exchanging mechanism is presented for energy trading between consumers. In [7], a two-stage optimal scheduling model is presented for the DERs based on the TE framework in RT and DA markets. In this study, DERs is considered in the form of virtual power plants (VPPs) and hourly scheduling of VPPs is optimized in DA and RT markets to maximize total profit and minimize imbalanced cost, respectively. TE technology is also effectively used in [8] to integrated nine renewable-based villages in the form of the smart rural network. In this research, managing the energy trading between villages and the power grid is accomplished based on the TE framework and three models are proposed for analyzing the villages energy cost minimization along with the energy not supplied. Given recent studies, one of the important objectives in the microgrid scheduling is the profit maximization from different perspectives. For instance, the optimal bidding strategy is computed for the renewable based microgrids in [9] to maximize expected profit in the DA market. In order to consider the uncertainties of the RERs, the authors have applied Monte Carlo simulation (MCS) and Kantorovich based methods for scenario generation and reduction, respectively. Optimal energy and reserve scheduling are being targeted in [10] by presenting a novel stochastic model for maximizing the microgrid operator's expected profit under the risk management strategy. Microgrid aggregator profit maximization has been considered as an objective function in [11] for determining the optimal hourly bids, which aggregator submits to the DA market. The Conditional Value at Risk (CVaR) method is also employed to deal with the different uncertainties in the mentioned study. Additionally, in [12], the microgrid operator is considered for expected profit maximization by presenting a risk-constrained stochastic framework and considering the uncertainties of RERs, electricity price and demand.

In the power system, radial distribution networks have a key role in supplying a large amount of energy to the consumers. Evaluation of these networks in the presence of new renewable-based DERs with various uncertainties would be essential in the converting process of present networks to the modern grids. However, not enough attention has been paid to this important issue in the power grid. In all of the mentioned researches, the microgrids have been not investigated for optimal scheduling of the DERs in the radial distribution system and reliable approach is not suggested effectively for the assessment of this problem in energy exchanging with the main grid. Therefore, in this paper, optimal scheduling of the DERs is targeted with microgrids profit maximization under the TE management in a 10-bus radial distribution system. Microgrids can submit the hourly bids/offers in the DA market to specify their energy consumption/production for the next energy exchanging day. Based on the submitted bids/offers from microgrids, they can become consumers when their bids are negative and play as producers, otherwise. This paper considers five commercial microgrids to evaluate the total profit maximization of the microgrid operator in the presence of RERs and controllable loads. Although energy trading can also be done in the VPPs, commercial microgrids, unlike the VPPs, have almost constant geographic size and energy devices, but the geographical size of VPPs can be varied based on the power grid status. Moreover, microgrids can be operated in both islanding and grid-connected modes while VPPs only can operate in the grid-connected mode. In this study, commercial microgrids are connected to the examined radial distribution system and each of them is equipped with wind turbines, PV panels, gas-fired diesel generators (DG) and battery energy storage systems (BESSs). Electricity price in the DA market and selling energy price are considered as uncertainties for this study. MCS method is applied for scenario generation and expected profit is computed for each microgrid. In this regard, normal distribution with a specific amount of mean and standard deviation has been used to generate various scenarios with different occurrence probabilities. Moreover, it is assumed that there are not any special correlations between generated scenarios in this work.

C. *Contributions and Organization*

Given the research gaps described in the third paragraph of subsection *B*, this paper proposes a TE management framework for maximizing the microgrids' profit in a regional network of microgrids. The novelties and main contributions of this research are as follows. 1) An energy trading based model is proposed for optimal scheduling of DERs in the radial distribution system integrated with a high level of clean energy production units. 2) TE technology is employed for managing and controlling the energy exchanging between microgrids and the main grid in a reliable manner. 3) Uncertainty modeling is carried out using the MCS approach for scenario generation process considering the various states of energy price occurrence in the DA electricity market.

The rest of this paper is organized as follows. In Section II, the optimization problem is formulated for the microgrids in the radial distribution network. Simulation results of this research are presented in Section III and finally, Section IV concludes the paper.

II. PROBLEM FORMULATION

In this section, first, the model of electricity price is presented in the DA market and then the profit-based objective function along with the constraints are explained in the next subsections.

A. *Electricity Price Model*

In the DA market, all of the selected microgrids submit the hourly bid/offer-quantity packages to the system operator where they are defined as producers (if $p_{t,s}^{Bid} > 0$) or consumer (if $p_{t,s}^{Bid} < 0$). In general, because of the stochastic load demand, it is expected that there will always be a deviation between the actual power and bid/offer in the microgrids. The deviation ($\Delta P_{t,s}^{D}$) and actual power ($P_{t,s}^{Act}$) can be formulated as follows:

$$\Delta P_{t,s}^{D} = P_{t,s}^{Act} - P_{t,s}^{Bid} \quad \forall \text{ t}, \forall \text{s} \tag{1}$$

$$P_{t,s}^{Act} = \sum_{i=1}^{M} (P_{i,t,s}^{W} + P_{i,t,s}^{DG} + P_{i,t,s}^{PV} + P_{i,t,s}^{BESS} + P_{i,t,s}^{IL}) - \sum_{j=1}^{N} P_{j,t}^{D} \tag{2}$$

The deviation between actual power in RT and bid/offer will impose extra costs for microgrids, which can be calculated as follows:

$$C_{t,s}^{D} = \begin{cases} \rho_{t,s}^{R+} . \Delta P_{t,s}^{D} & , \ \Delta P_{t,s}^{D} < 0 \\ \rho_{t,s}^{R-} . \Delta P_{t,s}^{D} & , \ \Delta P_{t,s}^{D} \geq 0 \end{cases} \tag{3}$$

Because of the existing correlation between DA and RT prices, the up and down regulation prices can be computed as a percentage of the DA market price as follows [13]:

$$\begin{cases} \rho_{t,s}^{R+} = (1+\sigma^{+}).\rho_{t,s}^{DA} \\ \rho_{t,s}^{R-} = (1-\sigma^{-}).\rho_{t,s}^{DA} \end{cases} \tag{4}$$

Equation (4) presents that microgrids should purchase (sell) their energy shortage (surplus) in the RT market at a higher (lower) price than the DA market price when $\Delta P_{t,s}^{D} < 0$ ($\Delta P_{t,s}^{D} \geq 0$).

B. *Objective Function*

In the DA market, each microgrid attempts to adopt an optimal bidding strategy over the scheduling process to maximize its own profit. The scenario-based objective function related to the optimal scheduling of DERs in the DA market is defined as follows:

$$\begin{aligned} F_i = \sum_{s=1}^{NS} \text{Pr}ob_s . \Bigg[& \sum_{t=1}^{T} P_{t,s}^{Bid} . \rho_{t,s}^{DA} . \Delta t + \sum_{t=1}^{T} \sum_{j=1}^{N} (P_{j,t}^{D} - P_{j,t,s}^{IL}) . \rho_{t,s}^{Sell} . \Delta t \\ & - \sum_{i=1}^{M} \sum_{t=1}^{T} \left(C_{i,t,s}^{DG} . X_{i,t,s}^{DG} + Csu_{i,t,s}^{DG} . X_{i,t,s}^{su} + Csd_{i,t,s}^{DG} . X_{i,t,s}^{sd} \right) \\ & + \sum_{t=1}^{T} C_{t,s}^{D} - \sum_{i=1}^{M} \sum_{t=1}^{T} (C_{i,t,s}^{IL} + C_{i,t,s}^{BESS}) \Bigg] \ \forall \ i \end{aligned} \tag{5}$$

In (5), the first term presents the revenue/cost of energy selling/purchasing to/from the distribution network. The second term represents the revenue of energy selling to consumers. The third and fourth terms state the energy cost of DG units and power imbalance. Finally, the last term is the cost of IL and BESS.

The costs of IL ($C_{j,t,s}^{IL}$) and DG ($C_{i,t,s}^{DG}$) are a function of $P_{j,t}^{IL}$ and $P_{i,t}^{DG}$, respectively, and they can be formulated by a quadratic polynomial function as follows [14]:

$$C_{j,t,s}^{IL} = \alpha_j^{IL}.(P_{j,t,s}^{IL})^2 + \beta_j^{IL}.P_{j,t,s}^{IL} \quad (6)$$

$$C_{i,t,s}^{DG} = \alpha_i^{DG}.(P_{i,t,s}^{DG})^2 + \beta_i^{DG}.P_{i,t,s}^{DG} + \gamma_i^{DG} \quad (7)$$

Finally, the operational cost of BESS is a linear function, which is dependent on the various characteristics of BESS and can be modeled as follows [15]:

$$C_{i,t,s}^{BESS} = \omega_i^{BESS}.P_{i,t,s}^{BESS}.\Delta t + \omega_i^{BESS}.E_{i,t,s}^{BESS}.\eta_L^{BESS}.\Delta t \quad (8)$$

$$\omega_i^{BESS} = \frac{ICB}{LCN.E_R^{BESS}} \quad (9)$$

Equation (8) presents that the operational cost of BESS typically refers to the maintenance cost, which is considered as the sum of charging/discharging and energy costs of BESS. Moreover, the cost coefficient related to the lifetime degradation of BESS is also represented in (9).

C. Constraints

All of the needed constraints related to (5) are formulated as follows:

1) Electricity Balance Constraint

$$\sum_{i=1}^{M}(P_{i,t,s}^{W} + P_{i,t,s}^{DG} + P_{i,t,s}^{PV} + P_{i,t,s}^{BESS}) = \sum_{j=1}^{N}(P_{j,t}^{D} - P_{j,t,s}^{IL}) + P_{t,s}^{Bid} + Ploss_{t,s} \quad \forall t, \forall s \quad (10)$$

$$Ploss_{t,s} = \sum_{j=1}^{N}\sum_{l=1}^{N} R_{j,l}.((V_{j,t,s} - V_{l,t,s})Y_{j,l})^2 \quad \forall t, \forall s \quad (11)$$

1) Wind Power Constraints

$$0 \le P_{i,t,s}^{W} \le P_{i,t,s}^{W,up} \quad \forall t, \forall s, \forall i \quad (12)$$

$$P_{i,t,s}^{W} / \sqrt{(P_{i,t,s}^{W})^2 + (Q_{i,t,s}^{W})^2} = \varpi \quad (13)$$

2) PV Panel Constraints

$$P_{i,t,s}^{PV} \le Spv_i.Sr_t.\eta^{pv} \quad \forall t, \forall s, \forall i \quad (14)$$

3) DG Constraints

$$X_{i,t,s}^{DG}.P_{i,t,s}^{DG,down} \le P_{i,t,s}^{DG} \le X_{i,t,s}^{DG}.P_{i,t,s}^{DG,up} \quad \forall t, \forall s, \forall i \quad (15)$$

$$P_{i,t,s}^{DG,up} \le P_{i,t}^{GD,dg}.Hr_{gas}.\Delta t \quad (16)$$

$$P_{i,t,s}^{DG} - P_{i,t-1,s}^{DG} \le R_i^{DG,up}, \text{ if } P_{i,t,s}^{DG} \ge P_{i,t-1,s}^{DG} \quad (17)$$

$$P_{i,t-1,s}^{DG} - P_{i,t,s}^{DG} \le R_i^{DG,down}, \text{ if } P_{i,t-1,s}^{DG} \ge P_{i,t,s}^{DG} \quad (18)$$

$$(T_{i,t-1,s}^{DG,on} - MUT_{i,s}^{DG}).(X_{i,t-1,s}^{DG} - X_{i,t,s}^{DG}) \ge 0 \quad (19)$$

$$(T_{i,t-1,s}^{DG,off} - MDT_{i,s}^{DG}).(X_{i,t-1,s}^{DG} - X_{i,t,s}^{DG}) \ge 0 \quad (20)$$

$$X_{i,t,s}^{DG} - X_{i,t-1,s}^{DG} \le X_{i,t,s}^{su} \quad (21)$$

$$X_{i,t-1,s}^{DG} - X_{i,t,s}^{DG} \le X_{i,t,s}^{sd} \quad (22)$$

$$X_{i,t,s}^{DG} - X_{i,t-1,s}^{DG} \le X_{i,t,s}^{su} - X_{i,t,s}^{sd} \quad (23)$$

Equation (15) presents the power generation limit of DG units. Equation (16) represents the dependency of the DG units' output to the gas availability. Ramp up and down limitations of DG units are stated in (17) and (18). Minimum up and down times of DG units are modeled by (19) and (20). Equations (21) to (23) are about the ON/OFF statuses of DG units [13].

4) BESS Constraints

$$E_{i,t+1,s}^{BESS} = E_{i,t,s}^{BESS} - (P_{i,t,s}^{BESS}.\Delta t) - (\left|P_{i,t,s}^{BESS}\right|.\eta_C^{BESS}.\Delta t) - (E_{i,t,s}^{BESS}.\eta_L^{BESS}.\Delta t) \quad \forall t, \forall s, \forall i \quad (24)$$

$$\mathrm{SOC}_{i,t,s}^{BESS} = E_{i,t,s}^{BESS} / E_R^{BESS} \quad (25)$$

$$\mathrm{SOC}_{i,t}^{BESS,\min} \le \mathrm{SOC}_{i,t,s}^{BESS} \le \mathrm{SOC}_{i,t}^{BESS,\max} \quad (26)$$

$$-Pchr_i^{BESS,\max} \le P_{i,t,s}^{BESS} \le Pdis_i^{BESS,\max} \quad (27)$$

$$Pchr_i^{BESS,\max} \ge 0 \; ; Pdis_i^{BESS,\max} \ge 0 \quad (28)$$

$$E_{i,0}^{BESS} = E_{i,In}^{BESS} \; ; E_{i,T}^{BESS} \ge E_{i,End}^{BESS} \quad (29)$$

Equation (24) models the energy balance of BESS. Equations (25) to (26) and (27) to (28) present the state-of-charge constraints and charging/discharging limitations of BESS, respectively [15].

5) Interruptible Load Constraints

$$\left|P_{j,t,s}^{IL}\right| \le P_{j,t}^{IL,\max} \quad \forall t, \forall s, \forall j \quad (30)$$

$$P_{j,t}^{D,\min} \le P_{j,t}^{D} - P_{j,t,s}^{IL} \le P_{j,t}^{D,\max} \quad (31)$$

6) Electricity Network Constraints

$$P_{j,t,s}^{Inj}(V_t, \theta_t) + P_{j,t}^{D} - P_{j,t,s}^{Gen} = 0 \quad \forall t, \forall s, \forall j \quad (32)$$

$$Q_{j,t,s}^{Inj}(V_t, \theta_t) + Q_{j,t}^{D} - Q_{j,t,s}^{Gen} = 0 \quad \forall t, \forall s, \forall j \quad (33)$$

$$S_{j,t,s}(V_t, \theta_t) \le S_{j,t,s}^{\max} \quad \forall t, \forall s, \forall j \quad (34)$$

$$V_j^{\min} \le V_{j,t,s} \le V_j^{\max} \quad \forall t, \forall s, \forall j \quad (35)$$

$$\theta_j^{\min} \le \theta_{j,t,s} \le \theta_j^{\max} \quad \forall t, \forall s, \forall j \quad (36)$$

Equations (32) to (33) state the alternative current (AC) power flow equations [13]. The limitations of complex power, voltage magnitude, and phase angle are considered in (34) to (36), respectively.

7) Electricity Exchanging Constraints

$$P_{exch}^{\min} \le P_{t,s}^{Bid} \le P_{exch}^{\max} \quad \forall t, \forall s \quad (37)$$

III. SIMULATION RESULTS

In this research, optimal scheduling of DERs is considered with the aim of microgrids profit maximization by adopting the optimal bidding strategy in the DA market under the TE management. This study is conducted on a 10-bus radial distribution network with a load profile adopted from [16]. Five commercial microgrids located in the Chicago area (U.S.) are selected for problem analyzing and all of them are operated in the grid-connected mode as shown in Fig. 1. Each microgrid is equipped with a wind turbine, PV panel, DG, and BESS. In addition, we assume that up to 10% of the load in each bus can be adjusted upon the system request. The total installed capacity of wind turbines is 6000 kW, and their specifications are available in [17]. The information about the time of use (TOU)-pricing scheme and the DA market prices can be found in [18]. Total energy generation for the DG units and PV panels are 8500 kW and 750 kW, respectively, and the solar radiation data is available in [19]. Other required information can also be found in [15, 20]. The complete set of information about the DG and BESS parameters are demonstrated in Table I and II, respectively. In this paper, electricity price is considered as an uncertain parameter and expected profit is also calculated for all microgrids.

TABLE I. PARAMETRS OF DIESEL GENERATORS

DG index	Min. (kW)	Max. (kW)	RU (kW/min)	RD (kW/min)	MUT (h)	MDT (h)
1	130	1750	7.5	7.5	2.5	2
2	160	2250	8	8.5	3	2.5
3	150	2000	8	8.5	3	2.5
4	75	1000	7	7	2	2
5	115	1500	8	8	3	2.5

TABLE II. PARAMETERS FOR EACH BATTERY STORAGE

Power Capacity	1000 (kW)	**Initial Energy**	400 (kWh)
Energy Capacity	4000 (kWh)	**Final Energy**	400 (kWh)
Energy Efficiency	91.4%	**Self-discharge**	3% per month
Investment Cost	800000 E_R^{BESS}	**Life Cycle**	1000

The existing binary variables related to the DG units and quadratic functions for computing the costs of IL and DG units have converted this problem to the MINLP problem. Hence, we use the SBB and DICOPT solvers in GAMS for solving this problem. After running the program, the same results are obtained for both the mentioned solvers, which indicates the reasonable level of the optimality for the simulation results. However, the global solution is not expected due to the type of this problem (MINLP). The numerical results of the problem are tabulated in Table III. The run time of this problem is 24.337 second and simulations of it were completed by a PC with Intel Core i7-6700HQ CPU @ 2.60 GHz with 16.00 GB RAM.

TABLE III. NUMERICAL RESULTS OF MICROGRIDS

Microgrid Index (M)	Cost of BESS ($)	Cost of DG unit ($)	Net profit ($)
M1	772.6	11829	8266.581
M2	765.8	14852	-700.953
M3	522.6	5217	6287.647
M4	1495.9	11073	-14018.035
M5	875.5	17848	-3830.700

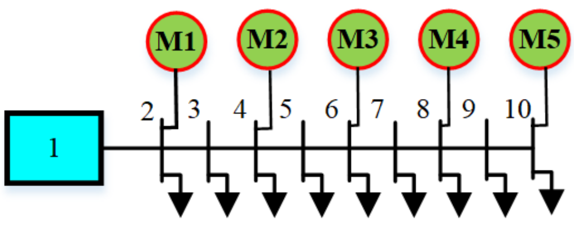

Fig. 1. Single line diagram of a 10-bus system with five microgrids

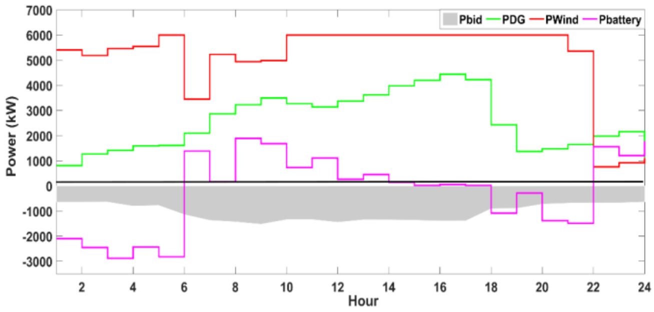

Fig. 2. Energy exchanging and scheduling of DG, BESS, and wind turbine

According to Table III, a positive amount of profit is not achieved for some microgrids. The cost of the produced energy in such microgrids is higher than their revenue, which led to a negative profit for them. In addition, mentioned microgrids such as M4 have transferred a large amount of energy to other buses to keep the power balance in the entire system. All grid-connected microgrids attempt to meet their demands and use the maximum of their energy production potentials to reduce the system dependency to the main grid. In this regard, the behaviors of DG units, BESS, and wind turbines in 24 hours are illustrated in Fig. 2. As seen in this figure, DG units and wind turbines have a maximum production at peak times (9-11 am and 13-17 pm). Because of the less energy consumption in the morning and at night, the surplus of generated energy is used for charging the BESSs while they are discharged in the afternoon and evening to help meeting demand when the energy consumption is at its highest level. In this regard, TE technology is effectively employed for managing the energy exchanging between the microgrids system and the main grid. In this study, the maximum amount of energy is traded at peak times.

In addition, PV panels are the other clean energy resources, which are considered for each microgrid. Since solar radiation at noon is higher than other times, hence, PV panels generate the maximum amount of energy in these times, which can help the system in meeting energy demand at peak times. Moreover, we assume that up to 10% of the load in each bus can be interrupted in necessary conditions. Because of the more energy consumption at peak times, some of the loads are interrupted to balance energy demand and supply. The operation of the PV panel and IL curves are demonstrated in Fig. 3.

In this study, BESSs are considered to mitigate the impacts of RERs uncertainties and used for energy storing when the electricity generation is greater than consumption. Also, to support the economic operation of the microgrids, BESSs are charged when the electricity selling price to the market is low while they are discharged at high-price periods not only to meet the local demands but also to exchange energy with the main grid for making a profit.

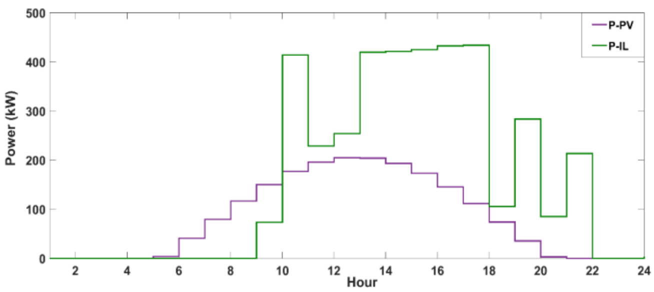

Fig. 3. PV panel scheduling and interrupted load magnitude

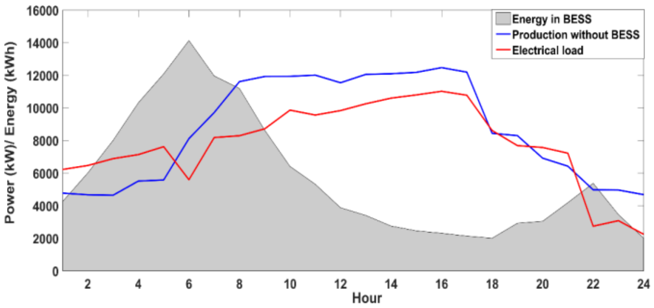

Fig. 4. Electricity produced without BESS and energy stored in BESS

The total electricity production without BESS along with the energy stored in BESS are shown in Fig. 4. As can be seen in this figure, the amount of energy in BESS is greater than other times because the electricity generation from wind turbines is high and its consumption is at its lowest level.

IV. Conclusion

This paper is structured to maximize microgrid profits with optimal scheduling of the DERs in the DA market. For realizing this goal, a TE approach was proposed to manage the energy exchanging with the main grid in a reliable manner while establishing a dynamic balance between the energy supply and demand throughout the system. Five grid-connected microgrids in a typical distribution system were considered as the case study where each microgrid was assumed to be equipped with clean energy resources such as wind and solar systems to reduce the negative effects of greenhouse gas emissions. In addition, electricity price in the market was considered as an uncertain parameter and numerous scenarios were generated using the MCS method. Finally, the simulation results were extracted and analyzed. It was observed that microgrids could get the most profit with optimal scheduling the DERs under the TE framework while some of them may have a negative profit based on their energy supplying strategy.

References

[1] J. Dulout, A. Luna, A. Anvari-Moghaddam, C. Alonso, J. Guerrero, and B. Jammes, "Optimal scheduling of a battery-based energy storage system for a microgrid with high penetration of renewable sources," in *ELECTRIMACS 2017*, 2017, p. 6p.

[2] J. Qiu, J. Zhao, H. Yang, and Z. Y. Dong, "Optimal scheduling for prosumers in coupled transactive power and gas systems," *IEEE Transactions on Power Systems,* vol. 33, no. 2, pp. 1970-1980, 2018.

[3] S. Leonori, E. De Santis, A. Rizzi, and F. F. Mascioli, "Multi objective optimization of a fuzzy logic controller for energy management in microgrids," in *Evolutionary Computation (CEC), 2016 IEEE Congress on*, 2016, pp. 319-326: IEEE.

[4] H. P. Khomami and M. H. Javidi, "Energy management of smart microgrid in presence of renewable energy sources based on real-time pricing," in *Smart Grid Conference (SGC), 2014*, 2014, pp. 1-6: IEEE.

[5] P. H. Divshali, B. J. Choi, and H. Liang, "Multi-agent transactive energy management system considering high levels of renewable energy source and electric vehicles," *IET Generation, Transmission & Distribution,* vol. 11, no. 15, pp. 3713-3721, 2017.

[6] M. H. Yaghmaee and A. Leon-Garcia, "A Fog-Based Internet of Energy Architecture for Transactive Energy Management Systems," *IEEE Internet of Things Journal,* 2018.

[7] J. Qiu, K. Meng, Y. Zheng, and Z. Y. Dong, "Optimal scheduling of distributed energy resources as a virtual power plant in a transactive energy framework," *IET Generation, Transmission & Distribution,* vol. 11, no. 13, pp. 3417-3427, 2017.

[8] M. Daneshvar, M. Pesaran, and B. Mohammadi-ivatloo, "Transactive Energy Integration in Future Smart Rural Network Electrification," *Journal of Cleaner Production,* 2018.

[9] M. J. Salehpour and S. M. M. Tafreshi, "Optimal bidding strategy for a smart microgrid in day-ahead electricity market with demand response programs considering uncertainties," in *Smart Grid Conference (SGC), 2017*, 2017, pp. 1-7: IEEE.

[10] M. Vahedipour-Dahraie, H. Rashidizadeh-Kermani, H. R. Najafi, A. Anvari-Moghaddam, and J. M. Guerrero, "Stochastic security and risk-constrained scheduling for an autonomous microgrid with demand response and renewable energy resources," *IET Renewable Power Generation,* vol. 11, no. 14, pp. 1812-1821, 2017.

[11] D. T. Nguyen and L. B. Le, "Risk-constrained profit maximization for microgrid aggregators with demand response," *IEEE Transactions on smart grid,* vol. 6, no. 1, pp. 135-146, 2015.

[12] M. Vahedipour, A. Anvari-Moghaddam, and J. Guerrero, "Evaluation of Reliability in Risk-Constrained Scheduling of Autonomous Microgrids with Demand Response and Renewable Resources," *IET Renewable Power Generation,* 2018.

[13] J. Qiu, J. Zhao, H. Yang, and Z. Y. Dong, "Optimal scheduling for prosumers in coupled transactive power and gas systems," *IEEE Transactions on Power Systems,* vol. 33, no. 2, pp. 1970-1980, 2017.

[14] E. Mashhour and S. M. Moghaddas-Tafreshi, "Bidding strategy of virtual power plant for participating in energy and spinning reserve markets—Part I: Problem formulation," *IEEE Transactions on Power Systems,* vol. 26, no. 2, pp. 949-956, 2010.

[15] F. Luo, Z. Y. Dong, K. Meng, J. Qiu, J. Yang, and K. P. Wong, "Short-term operational planning framework for virtual power plants with high renewable penetrations," *IET Renewable Power Generation,* vol. 10, no. 5, pp. 623-633, 2016.

[16] Y. Chen and M. Hu, "Balancing collective and individual interests in transactive energy management of interconnected micro-grid clusters," *Energy,* vol. 109, pp. 1075-1085, 2016.

[17] (2018, April 26). *Wind energy market intelligence*. Available: https://www.thewindpower.net/online_access_en.php

[18] L. Goel, P. Viswanath, and P. Wang, "Evaluation of probability distributions of reliability indices in a multi bilateral contracts market," in *Power System Technology, 2004. PowerCon 2004. 2004 International Conference on*, 2004, vol. 1, pp. 96-101: IEEE.

[19] M. Matos, J. Fidalgo, and L. Ribeiro, "Deriving LV load diagrams for market purposes using commercial information," in *Intelligent Systems Application to Power Systems, 2005. Proceedings of the 13th International Conference on*, 2005, pp. 105-110: IEEE.

[20] M. Daneshvar, M. Pesaran, and B. Mohammadi-ivatloo, "Transactive energy in future smart homes," in *The Energy Internet*: Elsevier, 2019, pp. 153-179.