tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و ...

Renewable Energy 123 (2018) 460–474

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Optimal energy management of a renewable-based isolated microgrid with pumped-storage unit and demand response

Ahmad Ghasemi [a, *], Mehdi Enayatzare [b]

[a] Department of Electrical and Computer Engineering, Jundi-Shapur University of Technology, Dezful, Iran
[b] Department of Electrical and Computer Engineering, Jundi-Shapur University of Technology, Dezful, Iran

ARTICLE INFO

Article history:
Received 14 September 2017
Received in revised form
5 January 2018
Accepted 15 February 2018
Available online 17 February 2018

Keywords:
Isolated microgrid
Photovoltaic power
Wind power
Pumped-storage power plant
Demand response
Energy management

ABSTRACT

This paper proposes a new stochastic optimization framework for day-ahead (DA) energy management of a renewable-based isolated rural microgrid. Non-dispatchable distributed generations (DGs) including wind and photovoltaic (PV) power plants have been operated by the microgrid in order to meet consumers' demand. The main challenge in this condition is to keep balance between generation and demand at all times. In order to cope with this challenge, a pumped-storage unit and an incentive-based demand response program have been used in this work. Moreover, the accurate model of pumped-storage unit, responsive demand and distribution network and also the inherent uncertainty of wind and PV power generation have been considered in this paper. Finally, the effectiveness of the proposed optimization framework has been evaluated through extensive numerical studies. The results show that the pumped-storage unit optimal scheduling and demand response implementation, significantly improve economic and technical performance indexes.

© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

1.1. Aim

Access to electricity is essential for sustainable economic and social development. However, around 17% of world's population, mostly living in rural areas, have no access to this source of energy [1]. Therefore, it has been a great challenge for governments to bring electricity to people living in these areas. The expansion of national grid to rural areas is not always technically and economically feasible and alternative solutions must be considered. In recent decade, generating electricity from renewable energy sources like wind and solar has been cost effective and considered as a viable solution. However, the electrical power generated from these resources is intermittent and non-dispatchable. This may make it difficult to keep balance between supply and demand in an isolated rural grid. Owing to smart grid deployment in recent years, it is possible to operate local distribution grids as a microgrid. A microgrid is a local energy grid consisting of distributed energy sources and loads which is capable to operate either in grid-connected or off-grid mode. The presence of smart grid technology in a microgrid makes it possible to implement modern energy management means like demand side management and demand response. Moreover, large scale energy reservoirs like pumped-storage power plants can be planned to work more efficiently in this environment. Optimal planning of energy reservoirs in addition to demand response implementation in an isolated microgrid can be a potential solution for supply-demand balance problem. The aim of this work is to study the effect of demand response implementation and pumped-storage optimal scheduling on energy management of a renewable-based isolated microgrid.

1.2. Literature review

Energy management of an isolated microgrid has attracted a great deal of attention in recent years. The main objective of most researches on stand-alone microgrid energy management is to meet energy demand of consumers located in the microgrid at the minimum cost. However, keeping balance between supply and demand when the microgrid is not connected to the main grid is a difficult task. The problem has been even worse with increasing deployment of uncertain renewable-based DGs. As a solution to this problem, dump load has been applied in a situation that

* Corresponding author.
E-mail addresses: aghasemi@jsu.ac.ir (A. Ghasemi), menayat@jsu.ac.ir (M. Enayatzare).

https://doi.org/10.1016/j.renene.2018.02.072
0960-1481/© 2018 Elsevier Ltd. All rights reserved.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

Nomenclature

Sets and indices

t	Sets of hours
i, j	Sets of buses
D	Set of aggregated demands (loads)
l	The number of uncertain variable

Variables

G_a^t	Irradiation of sun in hour t (W/m2)
T_a^t	Temperature in hour t ($^\circ C$)
$S_{G,PSU,i}^t$	Binary decision variable for the pumped-storage unit generation startup
$S_{P,PSU,i}^t$	Binary decision variable for the pumped-storage unit pump startup
$U_{P,PSU,i}^t$	Binary decision variable for the pumped-storage unit on/off status (Pump mode)
$U_{G,PSU,i}^t$	Binary decision variable for the pumped-storage unit on/off status (Generation mode)
$\Pi_{D0,i}^t$	Initial active power demand of aggregated load at bus i (MW)
$\Pi_{D,i}^t$	Active power demand of aggregated load at bus i (MW)
$\Pi_{P,PSU,i}^t$	Active power demand of the pumped-storage unit in the pump mode (MW)
$\Pi_{G,PSU,i}^t$	Active power generation of the pumped-storage unit in the generation mode (MW)
$Y_{G,PSU,i}^t$	Binary decision variable for the pumped-storage unit generation shut down
$Y_{P,PSU,i}^t$	Binary decision variable for the pumped-storage unit pump shut down
$q_{P,PSU,i}^t$	The amount of water charge of the pumped-storage unit (Hm^3/h)
$q_{G,PSU,i}^t$	The amount of water discharge of the pumped-storage unit (Hm^3/h)
$v_{PSU,i,up}^t$	The level of water in the upper reservoir (Hm^3)
$v_{PSU,i,dn}^t$	The level of water in the lower reservoir (Hm^3)
$\Pi_{G,i}^t$	Net active power injection to bus i (MW)
$\Psi_{G,i}^t$	Net reactive power injection to bus i (MVAr)
$\Psi_{D,i}^t$	Reactive power demand of aggregated load at bus i (MVAr)
Π_{Loss}^t	Total active power loss of the distribution network in hour t (MW)
Π_{EX}^t	Total excess power in hour t (MW)
$\Pi_{NS,i}^t$	Not supplied power at bus i (MW)
$\Pi_{PV,i}^t$	Active power generation of the Photovoltaic power plant (MW)
$\Pi_{Wind,i}^t$	Active power generation of the wind power plant (MW)
V_i^t	Bus i voltage magnitude (kV)
δ_i^t	Bus i voltage angle (rad)
S_{ij}^t	Apparent power flow from bus i to bus j (MVA)

Parameters

$\Pi_{Max,0}^M$	Maximum power of PV panel at the standard condition (kW)
G_{a0}	Irradiation of sun at the standard condition (W/m2)
$NOCT$	Normal operating cell temperature of PV system ($^\circ C$)
$T_{M,0}$	Module temperature at the standard condition ($^\circ C$)
$GSUC$	Startup cost of the pumped-storage unit in the generation mode ($)
$PSUC$	Startup cost of the pumped-storage unit in the pump mode ($)
$\Pi_{G,PSU,\max}^t$	The maximum power output of the pumped-storage unit in the generation mode
$NSPC$	Not supplied power cost ($/MW)
ρ_0	Base energy price ($/MWh)
$v_{PSU,i,up}^{\max}$	The maximum volume of water in the upper reservoir (Hm^3)
$v_{PSU,i,up}^{\min}$	The minimum volume of water in the upper reservoir (Hm^3)
$v_{PSU,i,dn}^{\max}$	The maximum volume of water in the lower reservoir (Hm^3)
$v_{PSU,i,dn}^{\min}$	The minimum volume of water in the lower reservoir (Hm^3)
$v_{PSU,i,up}^{init}$, $v_{PSU,i,dn}^{init}$	Initial volumes of the pumped-storage unit upper and lower reservoirs respectively (Hm^3)
$v_{PSU,i,up}^{fin}$, $v_{PSU,i,dn}^{fin}$	Final volumes of the pumped-storage unit upper and lower reservoirs respectively (Hm^3)
$q_{G,PSU,i}^{\max}$, $q_{G,PSU,i}^{\min}$	Water discharge limits of the pumped-storage unit (Hm^3/h)
$q_{P,PSU,i}^{\max}$, $q_{P,PSU,i}^{\min}$	Water charge limits of the pumped-storage unit (Hm^3/h)
$q_{Agri,i}^{\max}$, $q_{Agri,i}^{\min}$	Water discharge limits of the irrigation system (Hm^3/h)
θ_{ij}	Angles of complex Y-bus matrix elements (rad)
$V_i^{\max}$, $V_i^{\min}$	Maximum and minimum limits on bus voltages, respectively (kV)
$S_{ij}^{\max}$	Upper limit for apparent power flow from bus i to bus j (MVA)
a_{PSU}	The coefficient of the pumped-storage unit power conversion function ($MWh^2/(Hm^3)^2$)
b_{PSU}	The coefficient of the pumped-storage unit power conversion function ($MWh/(Hm^3)$)
c_{PSU}	The coefficient of the pumped-storage unit power conversion function (MW)

Function

C	Total cost ($)

generation exceeds demand [2–4]. Moreover, load shedding has been employed when demand exceeds generation [5,6]. However, using dump load and load shedding as conventional solutions, reduce the system efficiency and consumers' welfare respectively. Therefore, recent researches have focused on more sophisticated solutions like energy storages operation and demand response application in order to reduce drawbacks of the conventional solutions [7–10]. Energy management of a medium-voltage islanded microgrid has been studied in Ref. [11]. The optimization framework presented in Ref. [11] schedules dispatchable DGs and an energy storage system considering network equations and constraints. In Ref. [12] controllable loads have been applied to coordinate demand response, renewable energy sources and an energy storage system in a smart grid environment. Residential demand response modeling and valuation for renewable generation integration has been studied in Refs. [13,14]. Ref. [15] proposed a method to enhance resiliency of microgrids in the islanded mode using demand response. In this paper loads are prioritized as critical and non-critical loads [15]. During islanded operation, after supplying the critical loads, microgrid decides to provide energy to

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و ...

non-critical loads or to store excess energy for future dispatches [15]. Energy management of an islanded microgrid using demand response and energy storage considering renewable uncertainty has been studied in Ref. [7]. Ref. [16] proposed a new optimization framework for energy storage and demand response scheduling to minimize the imbalance cost of a distribution company [16]. In Ref. [17] the Hybrid Power Station (HPS) of Ikaria Island, Greece, has been introduced as the first wind-hydro-pumped-storage hybrid stations in the world. Moreover, a regulatory framework has been proposed for the HPS which is applicable for other isolated island grids [17]. A comparison between two main energy storage technologies, i.e. pumped-storage unit and battery energy storage, for a renewable energy powered microgrid on a remote island in Hong Kong has been presented in Ref. [18]. The results show that the joint operation of renewable energy system and pumped-storage unit is technically and economically feasible [18]. Furthermore, the joint operation shows practical potential for steady power supply in remote areas [18]. However, the uncertainty associated with renewables and demand response programs have not been taken into account in this work [18].

1.3. Contribution

The main contribution of this work is to propose a new energy management framework for a rural microgrid. The microgrid is not connected to the main grid and supplies its demand through non-dispatchable wind and PV power plants located in the microgrid. In order to keep balance between supply and demand and also maximizing renewable energy utilization, pumped-storage unit and demand response program have been implemented. Moreover, the uncertainty associated with wind and PV power generation has been modeled using the two point estimate method (TPEM). Furthermore, the accurate model of responsive demand and distribution network and also constraints related to power flow have been considered in this work.

1.4. Paper organization

The rest of this paper is organized as follows. In section 2 microgrid components and the proposed optimization framework are introduced. Mathematical formulation is presented in section 3. In section 4, several case studies, results and discussions are provided. Finally, the conclusion is given in section 5.

2. Problem description

2.1. Microgrid components

The microgrid considered in this paper is a medium voltage isolated microgrid located in a remote area. Energy demand of microgrid consumers is supplied from non-dispatchable wind and PV power plants. In order to keep balance between generation and demand, maximizing renewable energy utilization and reducing energy loss through dump loads, an energy storage system is applied. The microgrid is equipped with smart grid technology and has required infrastructures to implement demand response programs for energy management purposes. Fig. 1 shows the components and their connections of the isolated microgrid considered in this paper.

2.1.1. Energy storage system

The growing rise of renewable technologies, especially those with uncertain power generation like wind and PV, leads to need for a diversity of storage solutions to smooth intermittency and ensure secure supply. The type of these solutions directly depend on the resources and terrain of particular regions and locations. Among different electricity storage technologies, battery energy storage and pumped-storage system are more common and practical in the real world [19]. Therefore, these technologies have been analyzed and compared here from different points of view in order to justify the choice of pumped-storage system in this work.

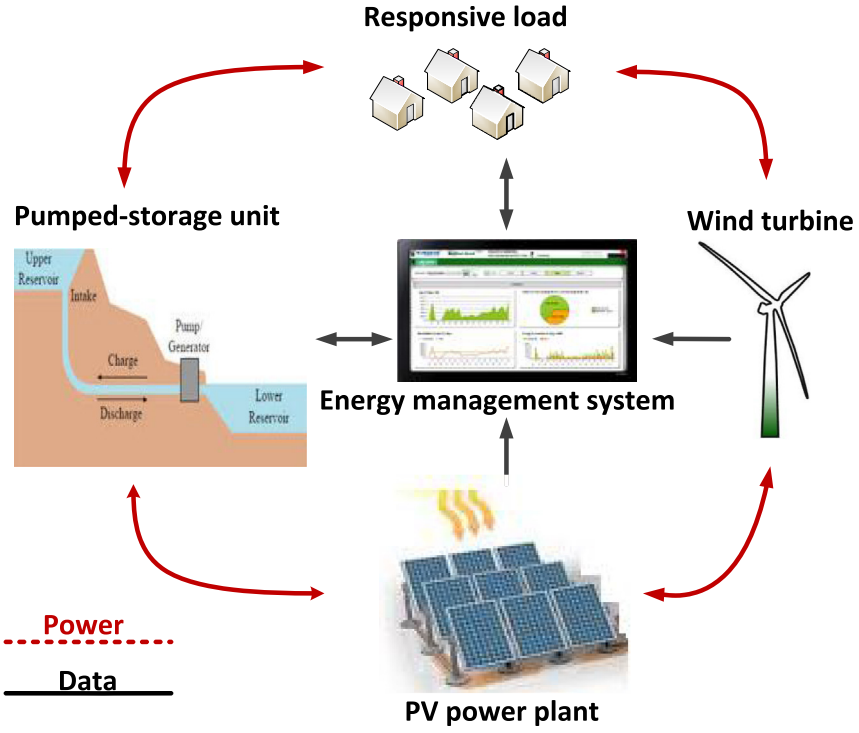

Fig. 1. The proposed optimization framework for isolated microgrid energy management.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و ...

From economic point of view according to the Lazard's Levelized Cost Of Storage (LCOS) report, capital costs for pumped-storage projects around the world range from about 213$ to 313$ per KW installed [20]. The report also reveals that the average cost of installing a mega-scale battery solution ranges from about 476$ to 1098.5$ [20]. Pumped hydro shows a very low operating cost per megawatt hour, ranging from about 152$/MWh to 198$/MWh [20]. Currently, battery average cost of operation range from 267$/MWh to nearly 561$/MWh [20].

From environmental point of view impacts of batteries are more related to their disposal at the end of their life, and to the extraction of the resources to produce new batteries [19]. Pumped-storage system may cause more environmental impact [19]. However, in most construction of new pumped-storage, sites are selected where impacts can be mitigated to acceptable levels [19].

From technical point of view batteries have shorter installation time, can provide fast response times and usually are located close to generation or load centers [19]. However, they have not demonstrated the ability to provide a full range of ancillary services needed to support the grid yet [19]. A particular consideration for batteries is degradation. Batteries degrade as they age, which decreases the amount of energy they can store [19]. To maintain a steady capacity for storage as batteries degrade, battery plants will require ongoing staged installation and replacement of batteries [19]. In comparison, pumped-storage system is a reliable technology and is able to meet the needs of the grid and provide sustained output for up to a century without degradation [19].

Finally, Refs. [17,18] confirm that the joint operation of a renewable energy system and pumped-storage system is technically and economically feasible and has practical potential for steady power supply in remote areas. Therefore, since the geographical features and terrain of the remote area considered in this paper are proper for pumped-storage power system installation and operation, this technology has been selected as storage system.

2.1.2. Wind power plant model

The power output of a wind turbine has a non-linear relationship with the wind speed. This relationship between power output and wind speed can be represented by using operational parameters of wind turbine. In this paper the model proposed in Ref. [21] has been used to define the relationship between the wind speed (v) and wind turbine power output ($\Pi^t_{Wind,i}(v)$). The hourly power output of a wind power plant as a function of the wind farm capacity (Cap_w), and the nominal 1-MW wind power output function is as follows [21].

$$\Pi^t_{Wind,i}(v) = Cap_w \times \begin{Bmatrix} 0 & 0 \le v \le v_i \\ a + bv^3 & v_i \le v \le v_r \\ 1 & v_r \le v \le v_o \\ 0 & v \ge v_o \end{Bmatrix} \quad (1)$$

where parameters a, and b are given as follows [19–23].

$$a = \frac{v_i^3}{v_i^3 - v_r^3} \quad (2)$$

$$b = \frac{1}{v_r^3 - v_i^3} \quad (3)$$

2.1.3. PV power plant model

In Ref. [22], it is assumed that the maximum power point tracking (MPPT) system has been always used to optimize PV system operation. The MPPT guarantees the PV system generates the maximum power for all temperatures and insulations [22]. The power output of a PV power plant ($\Pi^t_{PV,i}$) in each hour can be presented as follows [22].

$$\Pi^t_{PV,i} = \frac{G^t_a}{G_{a0}} \times \left\{ \Pi^M_{Max,0} + \mu_{\Pi\max} \times \left(T^t_a + G^t_a \times \frac{NOCT - 20}{800} - T_{M,0} \right) \right\} \quad (4)$$

Where, G_{a0} irradiation of sun at the standard condition, $\Pi^M_{Max,0}$ is the maximum power, $T_{M,0}$ is the temperature of the module at the standard condition and $NOCT$ is the normal operating temperature of cell.

3. Optimization framework

In order to optimally schedule DA operation of the microgrid, hourly demand profile must be estimated. Moreover, wind and PV power generation must be forecasted. Renewable based generation and demand forecast have been studied in different researches like Ref. [23] which is beyond the scope of this paper. In addition to demand profile and hourly generation, data of distribution network, pumped-storage unit and responsive demand elasticity must be considered. In summary, input and output data of the optimization framework shown in Fig. 2 are as follows.

Input data:

- Forecasted DA hourly generation of wind and PV power plants.
- Estimated DA hourly demand.
- Data of pumped-storage unit.
- Distribution network data.

Output data:

- DA scheduling of the pumped storage unit.
- Expected DA operation cost.
- Total excess energy and not supplied demand.

The TPEM has been used in this paper to model the inherent uncertainty associated with demand profile and renewable based generation.

3.1. Two point estimate method (TPEM)

The TPEM is known as a fast and accurate means for handling uncertainties [24]. This method only requires solving $2 \times m$ deterministic problems to obtain the behavior of m random variables [25]. Stochastic variables here are wind farm and photovoltaic unit power generation and initial hourly demand, assumed as uncorrelated variables. These variables are modeled as zero-mean normally-distributed random variables with standard deviation of σ [25].

In order to model the behavior of m stochastic variables, suppose P: $\{p_1, p_2, ..., p_l, ..., p_m\}$ is a random variable with a mean value μ and standard deviation σ. Z is also a random quantity in function of P: Z = F(P). Each of the k concentrations of the random variables p_l is defined as a concentration $p_{l,k}$ and a weight $w_{l,k}$ determined as follows.

$$p_{l,k} = \mu_{p_l} + \xi_{l,k}\sigma_{p_l} \quad (5)$$

where $\xi_{l,k}$ is the standard location of p_l and is computed as follows.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

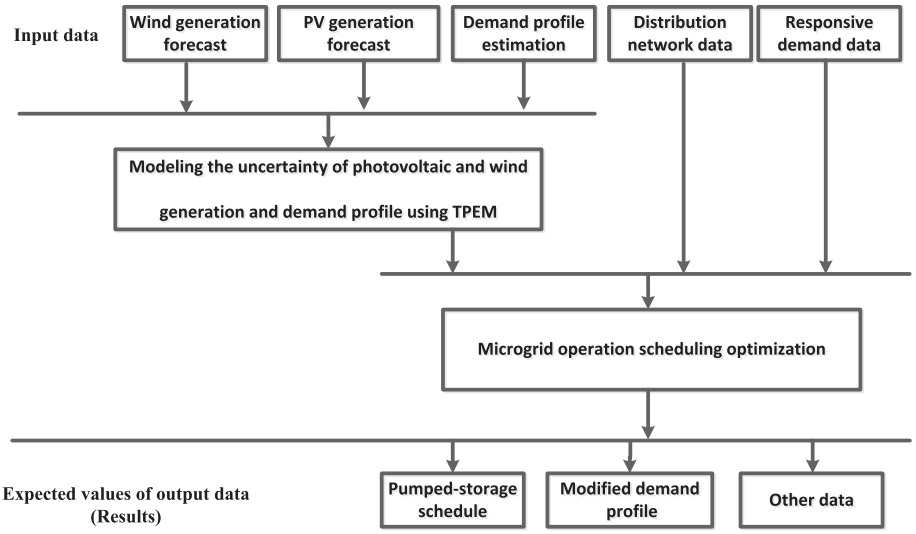

Fig. 2. The flow diagram of the proposed optimization framework.

$$\xi_{l,1} = \frac{\lambda_{l,3}}{2} + \sqrt{m + \left(\frac{\lambda_{l,3}}{2}\right)^2}$$
$$\xi_{l,2} = \frac{\lambda_{l,3}}{2} - \sqrt{m + \left(\frac{\lambda_{l,3}}{2}\right)^2} \quad (6)$$

and

$$w_{l,1} = -\frac{1}{m}\frac{\xi_{l,2}}{\xi_{l,1} - \xi_{l,2}}$$
$$w_{l,2} = \frac{1}{m}\frac{\xi_{l,1}}{\xi_{l,1} - \xi_{l,2}} \quad (7)$$

where $\lambda_{l,3}$ denotes the skewness of p_l:

$$\lambda_{l,3} = \frac{E\left[\left(p_l - \mu_{p_l}\right)^3\right]}{\left(\sigma_{p_l}\right)^3} \quad (8)$$

In each simulation, one of the concentrations with the other variables' means is taken into account to compute the statistical information of output variables.

$$Z_{l,k} = F\left\{p_{l,1}, p_{l,2}, \ldots, p_{l,k}, \ldots, p_{m,k}\right\} \quad (9)$$

$$E(Z) \cong E(Z) + \sum_k w_{l,k} \cdot Z_{l,k} \quad (10)$$

Detailed procedure of uncertainty modelling using the TPEM shown in Fig. 3 has been described in Ref. [24].

4. Mathematical formulation

The proposed optimization framework minimizes the operation cost of the microgrid. The model and constraints of the microgrid components including distribution network, responsive demand, wind and PV generation and pumped-storage have been implemented in the framework. Moreover, reserve and adequacy constraints have been taken into account.

4.1. Objective function

The objective function of the proposed optimization framework is the operation cost of the microgrid. The cost function (C) includes the operation cost of the pumped-storage power plant and the cost of not-supplied power ($\Pi^t_{NS,i}$). The pumped-storage power plant operation cost is associated with its startup cost in the generation and pump modes. The operation cost of wind and PV power plants is negligible and has not been considered in this work. Finally, the operation cost (objective function) minimized in the optimization process is presented as follows.

$$\min_{S^t_{PSU,i,G},\, S^t_{PSU,i,P}, \Pi^t_{NS,i}} C = \sum_t \left(GSUC \bullet S^t_{PSU,i,G} + PSUC \bullet S^t_{PSU,i,P} + NSPC \bullet \sum_i \Pi^t_{NS,i} \right) \quad (11)$$

Where $S^t_{PSU,i,G}$ and $S^t_{PSU,i,G}$ are binary decision variables for the pumped-storage unit startup in the generation and pump modes respectively. Furthermore, *GSUC* and *PSUC* are pumped-storage unit startup costs in the generation and pump modes respectively. *NSPC* is the cost of not-supplied power.

4.2. Constraints

The constraints included in the optimization framework are categorized in four groups. The first group consists of characteristics and constraints of the pumped-storage unit. The second group includes constraints and model of responsive demand. The third group contains adequacy and security constraints. The last group includes the constraints of distribution network and AC power flow.

4.2.1. Characteristics and constraints of the pumped-storage power plant

The pumped-storage power plant acts at one of the three modes of generating, pumping or offline at each time period. Water to power conversion equation and other constraints of the pumped-storage power plant are as follows.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

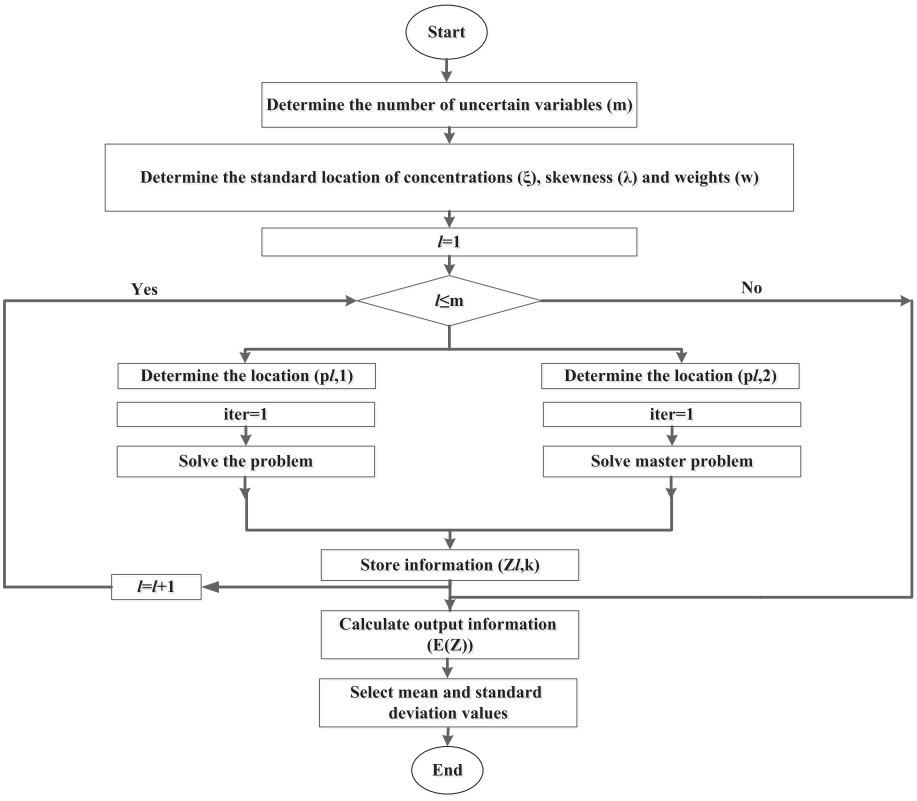

Fig. 3. Flowchart of the TPEM.

$$\Pi^t_{P,PSU,i} = a_{PSU}\left(q^t_{P,PSU,i}\right)^2 + b_{PSU}q^t_{P,PSU,i} + c_{PSU} \tag{12}$$

$$\Pi^t_{G,PSU,i} = a_{PSU}\left(q^t_{G,PSU,i}\right)^2 + b_{PSU}q^t_{G,PSU,i} + c_{PSU} \tag{13}$$

Where $q^t_{P,PSU,i}$ and $q^t_{G,PSU,i}$ are the amount of water charge and discharge of the pumped-storage unit in each hour respectively.

The amount of water stored in upper and lower reservoirs ($v^t_{PSU,i,up}$ and $v^t_{PSU,i,dn}$) are determined by Eqs. (14) and (15) respectively.

$$v^t_{PSU,i,up} = v^{t-1}_{PSU,i,up} - q^{t-1}_{G,PSU,i} + q^{t-1}_{P,PSU,i} + q^{t-1}_{Riv} \tag{14}$$

$$v^t_{PSU,i,dn} = v^{t-1}_{PSU,i,dn} + q^{t-1}_{G,PSU,i} - q^{t-1}_{P,PSU,i} - q^{t-1}_{Agri,i} \tag{15}$$

Capacity limits:

$$v^{\min}_{PSU,i,up} \le v^t_{PSU,i,up} \le v^{\max}_{PSU,i,up} \tag{16}$$

$$v^{\min}_{PSU,i,dn} \le v^t_{PSU,i,dn} \le v^{\max}_{PSU,i,dn} \tag{17}$$

Initial and final water volume

$$v^1_{PSU,i,up} = v^{init}_{PSU,i,up} \tag{18}$$

$$v^{24}_{PSU,i,up} \ge v^{fin}_{PSU,i,up} \tag{19}$$

$$v^1_{PSU,i,dn} = v^{init}_{PSU,i,dn} \tag{20}$$

$$v^{24}_{PSU,i,dn} \ge v^{fin}_{PSU,i,dn} \tag{21}$$

Water charge and discharge limits

$$q^{\min}_{G,PSU,i} \bullet U^t_{G,PSU,i} \le q^t_{G,PSU,i} \le q^{\max}_{G,PSU,i} \bullet U^t_{G,PSU,i} \tag{22}$$

$$q^{\min}_{P,PSU,i} \bullet U^t_{P,PSU,i} \le q^t_{P,PSU,i} \le q^{\max}_{P,PSU,i} \bullet U^t_{P,PSU,i} \tag{23}$$

Constraints (24) and (25) ensures that the relationship between generation/pump binary variables are logical.

$$Y^t_{G,PSU,i} - S^t_{G,PSU,i} = U^t_{G,PSU,i} - U^{t-1}_{G,PSU,i} \tag{24}$$

$$Y^t_{P,PSU,i} - S^t_{P,PSU,i} = U^t_{P,PSU,i} - U^{t-1}_{P,PSU,i} \tag{25}$$

Where U, S and Y are binary decision variables for pumped-storage unit status (on/off), startup and shout down respectively.

4.2.2. The model and constraints of responsive demand

A comprehensive economic model of responsive demand is derived in Ref. [26] based on load characteristics including price elasticity and demand profile. This model has been modified in this paper for a responsive demand in time interval t and has been presented in (Eq. (26)). The elasticity coefficient $e^t_{D,i}$ in (Eq. (26)) shows consumers' willingness to change their demand in response to incentives (INC^t) and penalties (PEN^t) determined and sent by microgrid operator. The more willingness of consumers to shift their demand results in larger values of $\left|e^t_{D,i}\right|$.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

$$\Pi^t_{D,i} = \Pi^t_{D0,i}\left\{1 + e^t_{D,i}\cdot\left[\frac{PEN^t - INC^t}{\rho_0}\right]\right\} \quad (26)$$

Where $\Pi^t_{D0,i}$ and $\Pi^t_{D,i}$ are initial and final demands of aggregated load at bus i respectively.

The maximum daily energy demand reduction or increment of responsive consumers has been limited to 5% of initial estimated consumers' demand.

$$0.95 \times \sum_t \Pi^t_{D0,i} \le \sum_t \Pi^t_{D,i} \le 1.05 \times \sum_t \Pi^t_{D0,i} \quad (27)$$

4.2.3. Security and adequacy constraints

The constraints of supply-demand balancing

$$\Pi^t_{Wind,i} + \Pi^t_{PV,i} + \Pi^t_{G,PSU,i} + \sum_i \Pi^t_{NS,i} = \sum_i \Pi^t_{D,i} + \Pi^t_{Loss} + \Pi^t_{P,PSU,i} + \Pi^t_{EX} \quad (28)$$

Where $\Pi^t_{Wind,i}$, $\Pi^t_{PV,i}$, $\Pi^t_{G,PSU,i}$ and Π^t_{Loss} are wind power generation, PV power generation, pumped-storage power generation and power loss of the network respectively. Moreover, $\sum_i \Pi^t_{NS,i}$ and Π^t_{EX} are hourly not supplied power and excess power respectively.

4.2.4. Reserve capacity

Because of possible variations in PV and wind power generation and also load demand, this is necessary to ensure that enough capacity exists in each hour. Thus, (γ%) (e.g. 5% based on data of wind and PV power generation and (χ%) (e.g. 2% based on information given in Ref. [27]) of total demand in each hour is considered as the reserve margin provided by the pumped-storage power plant. Pumped-storage unit has been supposed to benefit from a variable speed pump/turbine in this work. Therefore, it has the ability to be operated as a slack generator in order to maintain the power balance [28]. Moreover, wind and PV power plants have been modeled as PQ generator in this work.

$$\Pi^t_{PS,G,\max} - \Pi^t_{PS,G,i} + \Pi^t_{PS,P,i} \ge \chi \bullet \left(\Pi^t_{Wind,i} + \Pi^t_{PV,i}\right) + \gamma \bullet \sum_D \Pi^t_{D,i} \quad (29)$$

4.2.5. Network constraints

Power flow equations

$$\Pi^t_{G,i} - \Pi^t_{D,i} = \sum_j |V^t_i|\left|Y^t_{ij}\right|\cos\left(\theta_{ij} + \delta^t_j - \delta^t_i\right) \quad (30)$$

$$\Psi^t_{G,i} - \Psi^t_{D,i} = \sum_j |V^t_i|\left|Y^t_{ij}\right|\sin\left(\theta_{ij} + \delta^t_j - \delta^t_i\right) \quad (31)$$

where $\Pi^t_{G,i}$ is calculated as follows.

$$\Pi^t_{G,i} = \Pi^t_{Wind,i} + \Pi^t_{PV,i} + \Pi^t_{G,PSU,i} + \Pi^t_{NS,i} - \Pi^t_{P,PSU,i} \quad (32)$$

Bus voltage limit

$$V^{\min}_i \le V^t_i \le V^{\max}_i \quad (33)$$

Feeder flow limit

$$S^t_{ij} \le S^{\max}_{ij} \quad (34)$$

5. Numerical studies

In this section microgrid components data and other required data for performing numerical studies have been presented. Then, the results of four case studies performed to evaluate the effectiveness of the proposed framework have been presented and analyzed. The microgrid contains a wind power plant, a PV power plant and a pumped-storage unit scheduled to supply microgrid energy demand. Moreover, consumers in the microgrid participate in incentive-based demand response programs implemented by the microgrid operator.

5.1. Data

The single diagram of microgrid distribution network with feeders' data are presented in Fig. 4. The data of the pumped-storage unit located at bus 1 are given in Table 1. Furthermore, a wind power plant as a stochastic DG is located at bus 11. Moreover a PV power plant as a non-dispatchable DG is located at bus 6. The mean value and standard deviation (St. De) of wind and PV forecasted power generation and estimated demand are presented in Tables 2–4 respectively.

Different time intervals considered in this work are shown in Fig. 5. The values of incentive, penalty and elasticity coefficient have been set to 5$, 5$ and −0.1 respectively based on information given in Ref. [29] with some modifications. Moreover, the maximum power demand reduction or increment of responsive consumers has been limited to 5% of initial estimated consumers' demand. The cost of not-supplied energy has been set to 20$ per each megawatt hour. In addition, the base price (ρ_0) in responsive demand model (Eq. (26)) has been set to 20$.

6. Results and discussion

In order to evaluate the effectiveness of the proposed energy management framework, four case studies have been performed in this section. Demand response and pumped-storage unit are two potential options which can be used to keep generation and demand in balance at all times. In case #1 demand response has not been implemented and the pumped-storage unit has been supposed to be in offline mode. In case #2 demand response has not been implemented, but the pumped-storage unit has been planned to be operated. In case #3 incentive-based demand response program has been implemented while the pumped-storage unit has been set to offline mode. In case #4 demand response program has been implemented and the pumped-storage unit has been planned to be operated. Finally, the impact of consumers' elasticity level on the effectiveness of the proposed demand response program in cases #3 and #4 has been studied. These case studies have been solved in General Algebraic Modelling System (GAMS) using the SBB solver [30]. The SBB is a GAMS solver used for Mixed Integer Nonlinear Programming (MINLP) models working based on the standard Branch and Bound method [30]. The simulation has been run six times for each case to model the uncertainty associated with wind and PV power and demand profile, based on the TPEM. The computation time (mean value) on a core IV PC, 2.6 MHz with 4 GB of RAM for cases #1, #2, #3 and #4 is 6.20s, 8.37s, 3.04s and 9.05s respectively. It should be noted that since input data like wind and PV generation and demand and also the optimization framework are stochastic, the results are

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

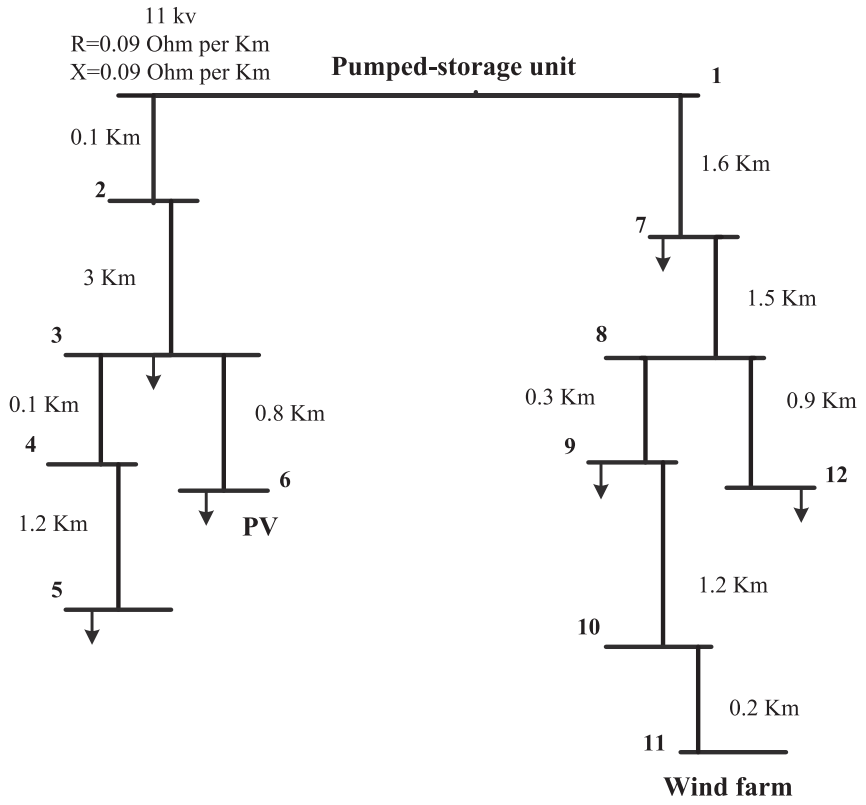

Fig. 4. The microgrid distribution network.

Table 1
Characteristics of pumped-storage unit.

Upper reservoir				Lower reservoir				Lower limit charge/discharge (Hm^3/h)	Upper limit charge/discharge (Hm^3/h)
Lower limit volume (Hm^3)	Upper limit volume (Hm^3)	Initial volume (Hm^3)	Terminal volume (Hm^3)	Lower limit volume (Hm^3)	Upper limit volume (Hm^3)	Initial volume (Hm^3)	Terminal volume (Hm^3)		
0.05	0.4	0.15	0.15	0.1	0.6	0.4	0.4	0.01	0.06

a_{PSU} (MW $h^2/(Hm^3)^2$)	b_{PSU} (MW h/Hm^3)	c_{PSU} (MW)	Min on (h)	Min off (h)	Gen. Start up. cost ($)	Pump Start up. cost ($)
−0.033	5	0	1	1	10	15

Table 2
DA generation forecast of wind power plant.

Hour	Wind power	
	Mean (MW)	St. De (MW)
t = 1,…,4	0.29	0.01
t = 5,…,8	0.38	0.02
t = 9,…,12	0.44	0.03
t = 13,…,16	0.47	0.02
t = 17,…,20	0.42	0.02
t = 21,…,24	0.36	0.01

probabilistic and have been presented in the form of mean value.

In Fig. 6 the total hourly demand profile in four case studies has been presented. In cases #1 and #2 demand response has not been implemented and therefore demand profile is the same in both cases. However, in cases #3 and #4 demand has been reduced in peak hours while it has been increased in off-peak hours. It should be noted that the total demand in cases #3 and #4 has been reduced about 3% which is well below the maximum limit (5%).

Figs. 7 and 8 respectively show optimal pump and generation scheduling of the pumped-storage power plant in cases #2 and #4. As it can be seen from Fig. 7 the generated power in case #4 is less than case #2. The main reason of this fact is that demand response implemented in case #4 has reduced the demand in this case. Fig. 8 shows that the pumped-storage unit works in the pump mode mostly in off and mid-peak hours in both cases #2 and #4 in order to charge the upper reservoir. Water charge/discharge of the pumped-storage power plant have been presented in Figs. 9 and 10 respectively. The trend of water charge and discharge follows pump and generation scheduling of the pumped-storage unit.

The total water remaining in the upper and lower reservoirs in each hour have been shown in Figs. 11 and 12 respectively. In cases #1 and #3 the pumped-storage unit has not been operated and therefore the level of water in the upper and lower reservoirs remains unchanged. In addition, the level of water in the last hour in both reservoirs is equal to the first hour in cases #2 and #4 in order to satisfy the operational constraints. It should be noted that the hours of water charge and discharge of the pumped-storage power plant are continuous. The main reason of this fact is to avoid pump/generation startup costs.

Fig. 13 shows the excess power generation during each hour of the day. According to Fig. 13, in case #4 water charge is scheduled to

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

Table 3
DA generation forecast of PV power plant.

Hour	PV power	
	Mean (MW)	St. De (MW)
t = 1	0	0.0
t = 2	0	0.0
t = 3	0	0.0
t = 4	0	0.0
t = 5	0	0.0
t = 6	0.019	0.001
t = 7	0.039	0.001
t = 8	0.068	0.002
t = 9	0.077	0.002
t = 10	0.105	0.002
t = 11	0.126	0.003
t = 12	0.133	0.004
t = 13	0.13	0.004
t = 14	0.13	0.003
t = 15	0.11	0.003
t = 16	0.08	0.003
t = 17	0.058	0.002
t = 18	0.029	0.002
t = 19	0.01	0.001
t = 20	0	0
t = 21	0	0
t = 22	0	0
t = 23		
t = 24	0	0

Table 4
Total hourly demand.

Hour	Demand power	
	Mean (MW)	St. De (MW)
t = 1	0.204	0.0
t = 2	0.0595	0.001
t = 3	0.068	0.0
t = 4	0.1275	0.0
t = 5	0.221	0.0
t = 6	0.357	0.002
t = 7	0.51	0.0
t = 8	0.51	0.01
t = 9	0.51	0.0
t = 10	0.51	0.005
t = 11	0.51	0.01
t = 12	0.51	0.03
t = 13	0.51	0.02
t = 14	0.4675	0.005
t = 15	0.357	0.01
t = 16	0.357	0.01
t = 17	0.425	0.02
t = 18	0.50575	0.02
t = 19	0.68	0.02
t = 20	0.9095	0.005
t = 21	0.8245	0.002
t = 22	0.5525	0.0
t = 23	0.3995	0.0
t = 24	0.238	0.0

be shifted to mid-day hours like 10–18 to reduce excess power generation in this hours. Although the excess power generation in case #4 has been shifted to early hours in the morning, Fig. 14 confirms that total excess generation is still less than other cases. This is due to demand response implementation and pumped-storage optimal operation in case #4.

Fig. 15 shows not supplied power during each hour of the day. As seen from Fig. 15, not supplied power has the maximum value during peak hours (18–23) in most cases which is sensible. However, Fig. 16 shows that demand response implementation in case #3 reduces not supplied power in comparison with initial case #1. Moreover, the optimal operation of the pumped-storage unit in cases #2 and #4 reduces not supplied power even more than case #3. However, the most reduction in not supplied power has been happened in case #4 with demand response and pumped-storage unit. From Figs. 14 and 16 it can be understood that the impact of demand response implementation and pumped-storage unit operation on not supplied power reduction is more than excess power reduction in case #4. This is due to the fact that the cost of not supplied power has been considered in the objective function in order to reduce consumers' inconvenience. Moreover, not supplied energy in case #4 have the smallest value among all case studies. Furthermore, the operation of the pumped-storage unit in case #2 with the aim of not supplied energy and excess energy reduction are more effective than demand response implementation in case #3.

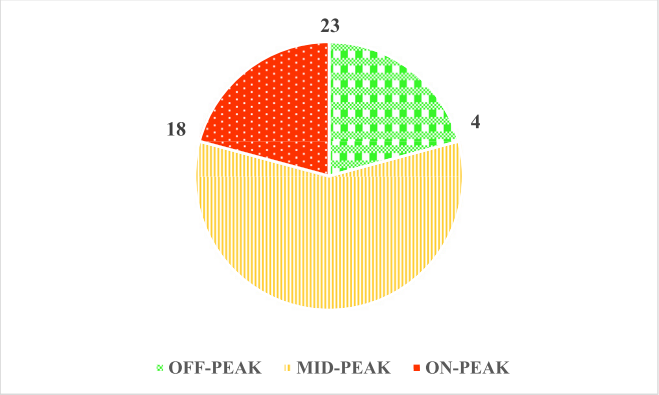

Fig. 5. Time intervals.

In this paper the total cost has been considered as economic performance index and the summation of energy not supplied and excess energy absolute values has been defined as technical performance index. The performance index and total operation cost of four cases studied in this paper have been shown in Figs. 17 and 18 respectively. According to Fig. 17, case #4 benefiting from demand response implementation and pumped-storage unit optimal operation has the best technical performance index. Moreover, Fig. 18 shows that case #4 with both demand response and pumped-storage unit has the lowest operation cost.

Finally, in order to evaluate the impact of consumers' elasticity level on the proposed demand response program effectiveness, the economic and technical performance indexes in cases #3 and #4 have been calculated for different values of elasticity coefficients. Figs. 19 and 20 show that the total cost (economic performance index) is reduced and technical performance index is improved when the elasticity level of responsive consumers is increased. This is due to the fact that the higher levels of responsive consumers' elasticity, reduces the distance between peak and off-peak demand which in turn increases the effectiveness of the proposed program. Therefore, efforts to increase the consumers' elasticity through informing and educating them can improve the economic and technical performance indexes of microgrid energy management.

7. Conclusion

The energy management of a renewable-based rural microgrid has been studied in this paper. The microgrid is not connected to the main grid and supplies its demand through non-dispatchable DGs including wind and PV power plants. In order to keep balance between generation and demand at all times a pumped-storage unit and an incentive-based demand response have been implemented. Moreover, a new optimization framework has been

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و...

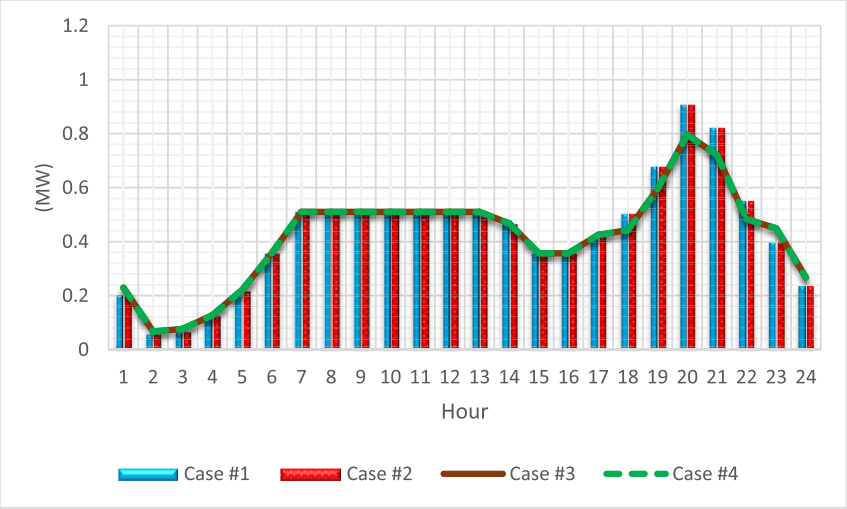

Fig. 6. Total hourly demand.

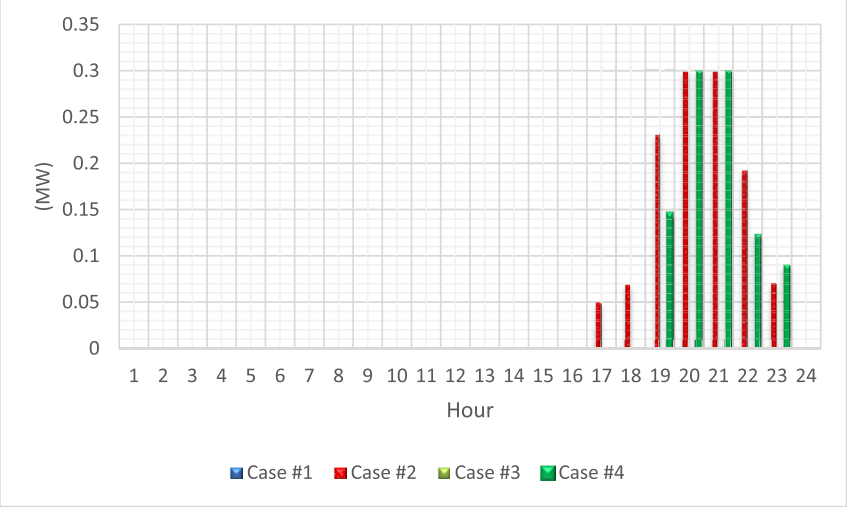

Fig. 7. Optimal generation schedule of the pumped-storage unit.

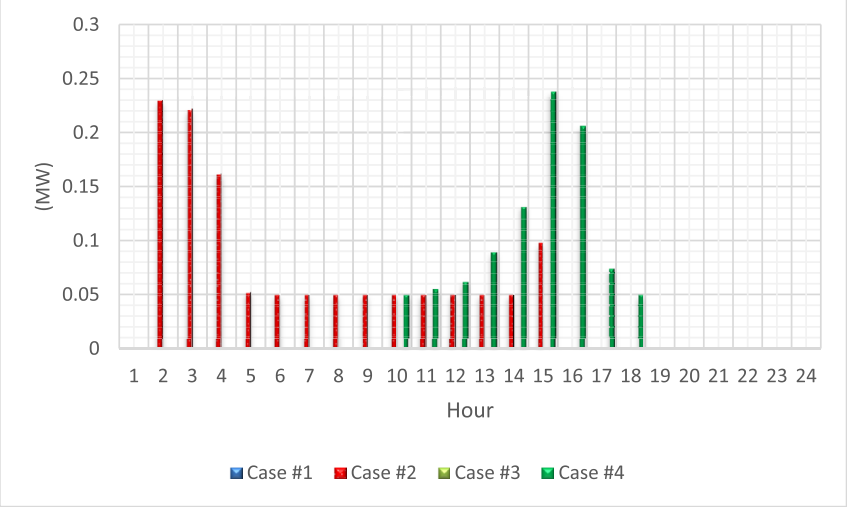

Fig. 8. Optimal pump schedule of the pumped-storage unit.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و...

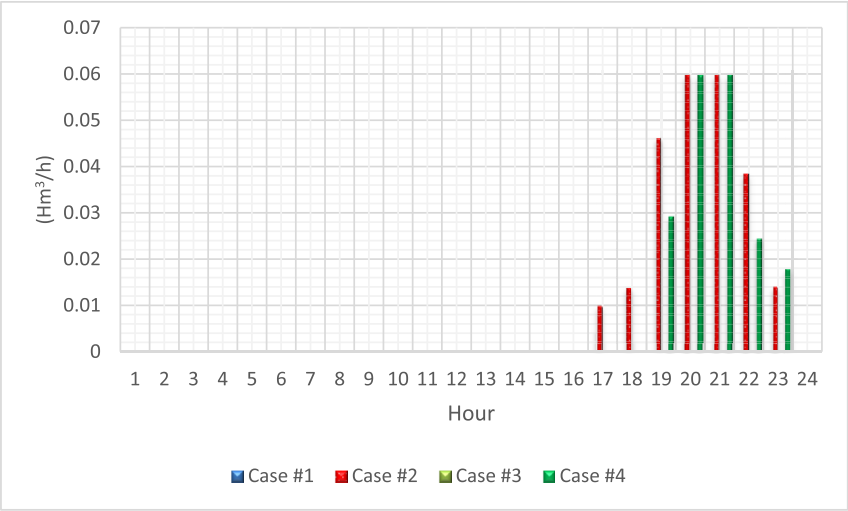

Fig. 9. The water hourly discharged from the upper reservoir.

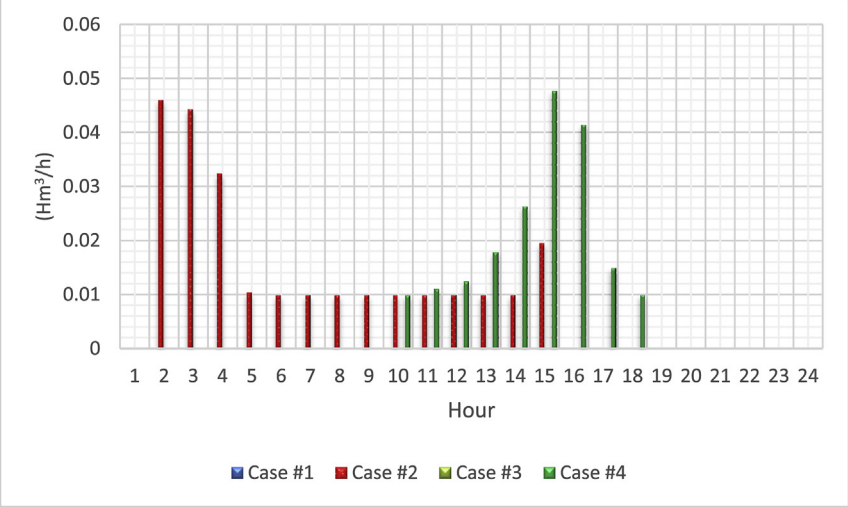

Fig. 10. The water hourly pumped to the upper reservoir.

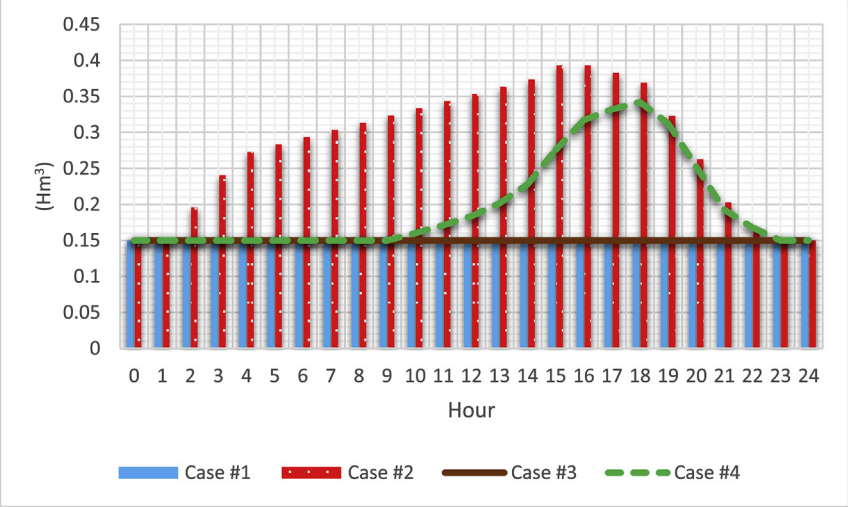

Fig. 11. The level of water in the upper reservoir.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و...

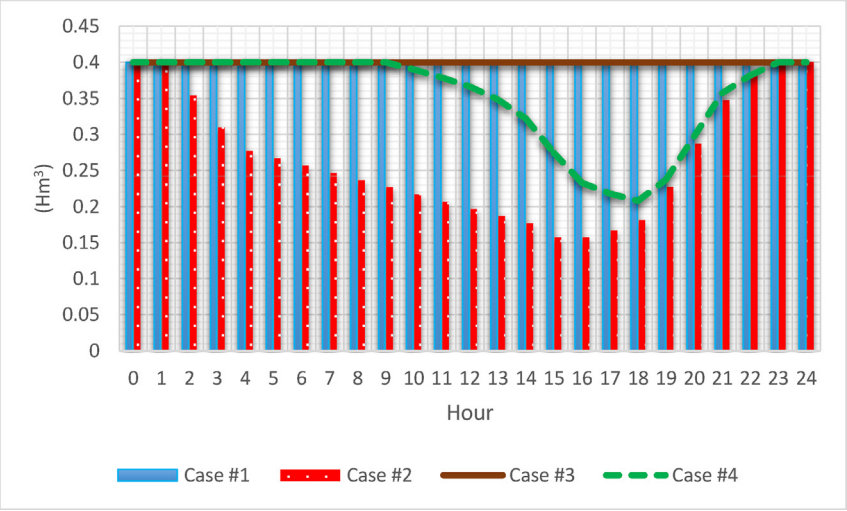

Fig. 12. The level of water in the lower reservoir.

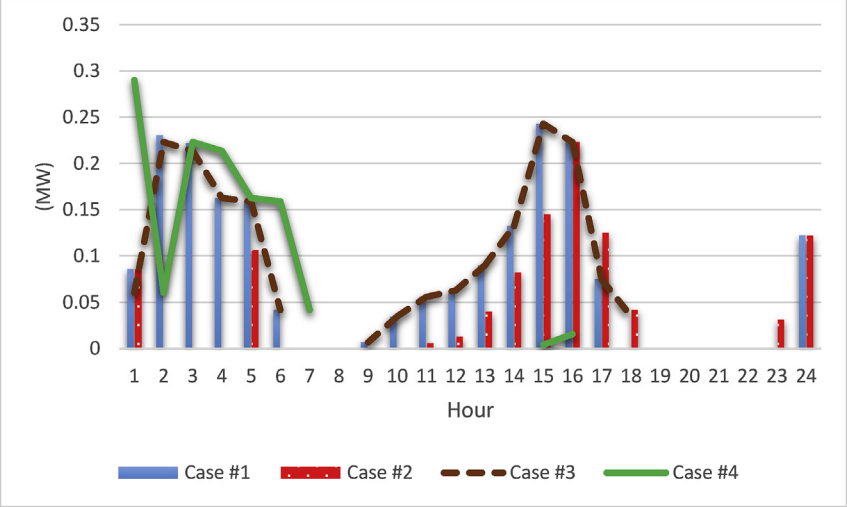

Fig. 13. The excess power.

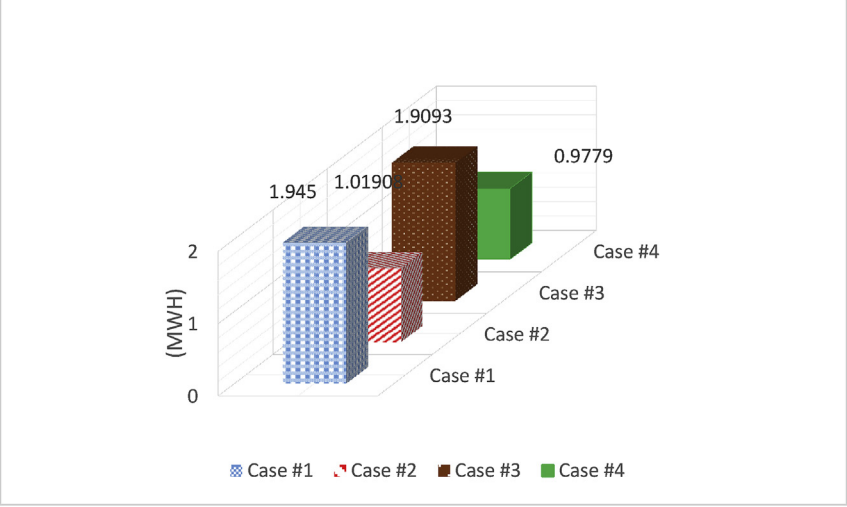

Fig. 14. The excess energy.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و...

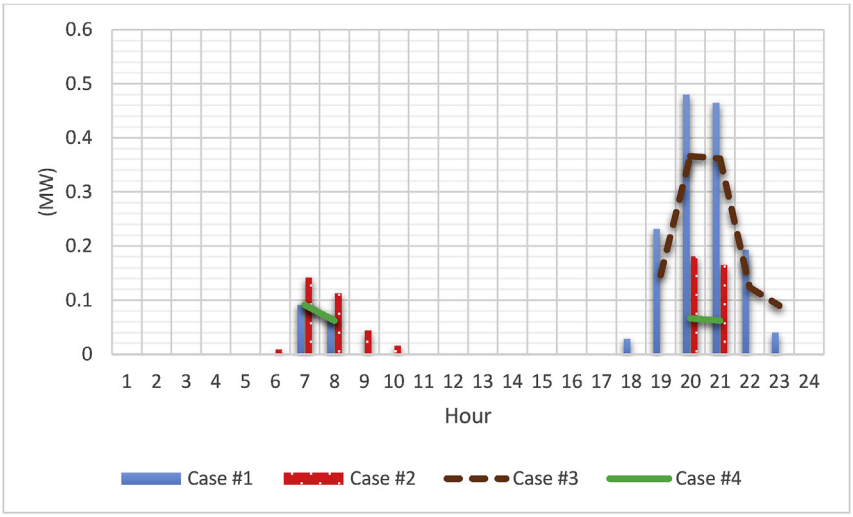

Fig. 15. The not supplied power.

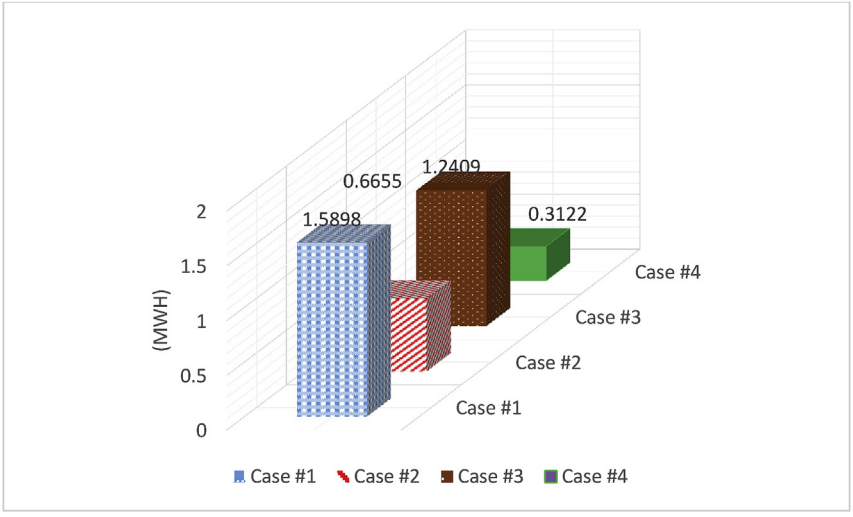

Fig. 16. The not supplied energy.

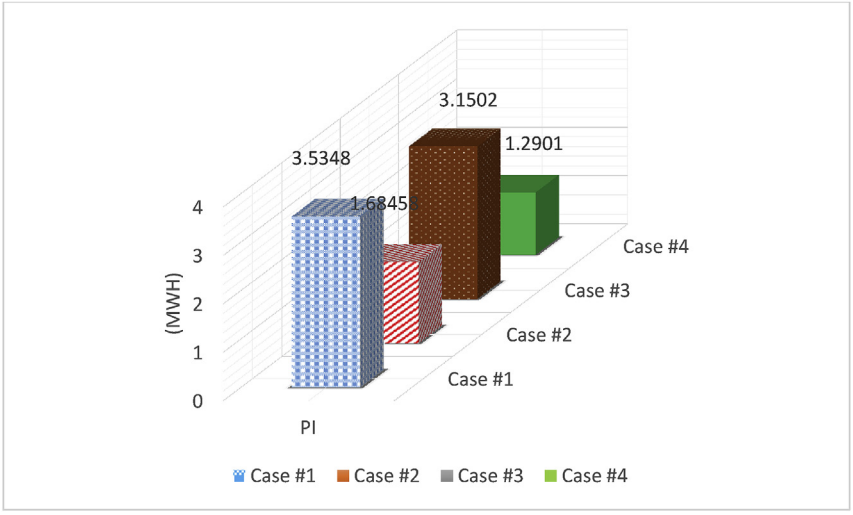

Fig. 17. The technical performance index.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها متلب گمز و...

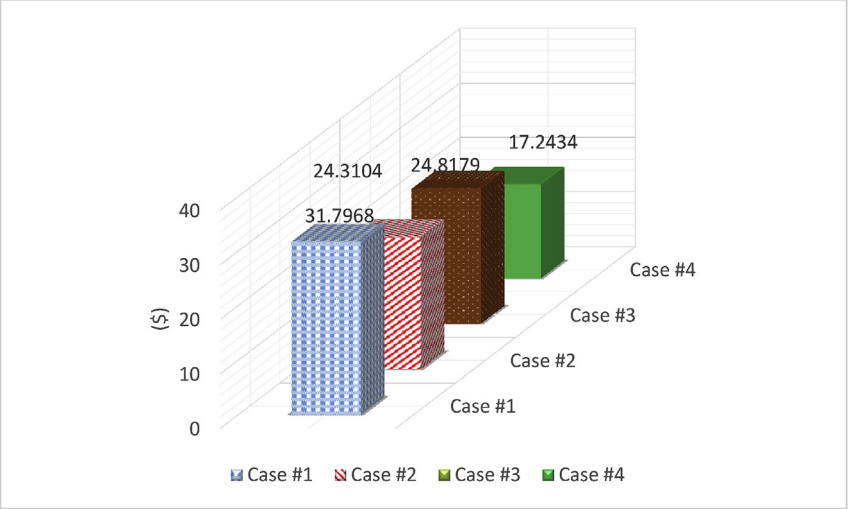

Fig. 18. The operation cost.

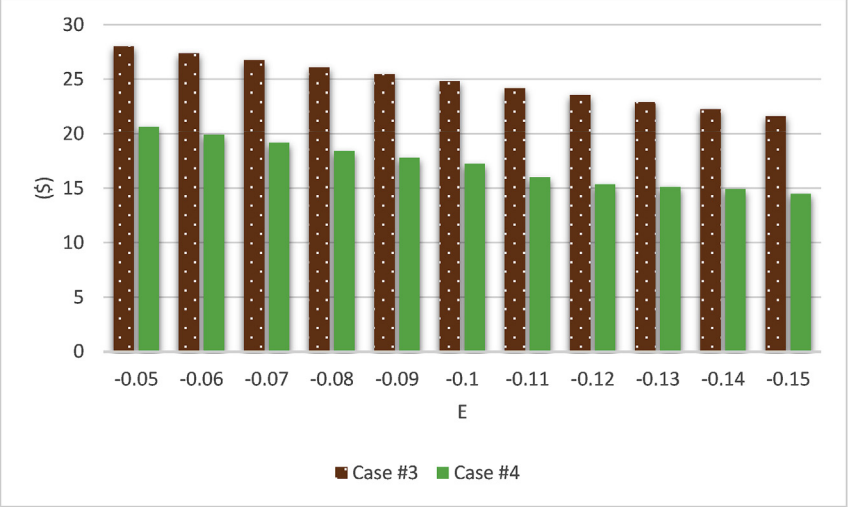

Fig. 19. The economic performance index vs. elasticity coefficient value.

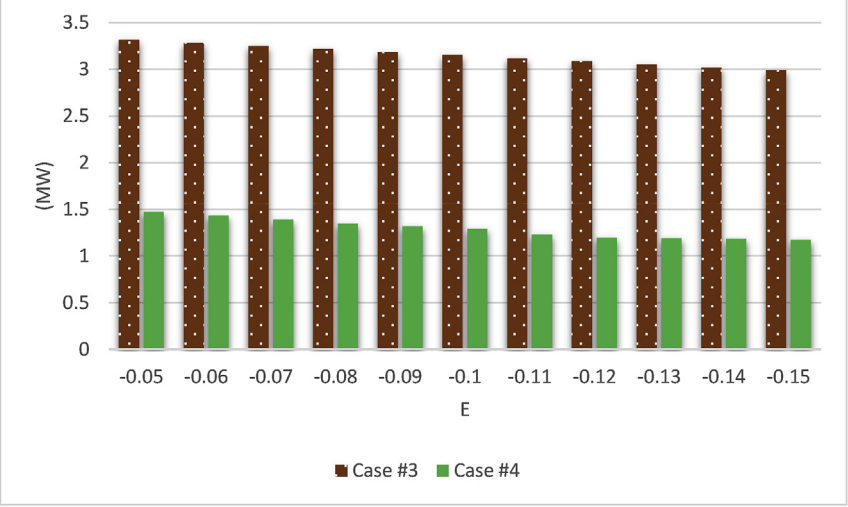

Fig. 20. The technical performance index vs. elasticity coefficient value.

tarjomehrooz.com 0902 795 28 76 ترجمه تخصصی توسط دکتری رشته مربوطه و برای کلیه زبان های خارجی + شبیه سازی مقالات با کلیه نرم افزار ها مثلب گمز و ...

proposed to optimally schedule DA operation of the pumped storage unit. Furthermore, the uncertainty of wind and PV power generation and also the accurate model of pumped-storage unit, responsive demand and distribution network have been considered in this paper. In order to validate the effectiveness of the proposed framework, demand response and pumped storage unit have been implemented in different cases. The results show that pumped-storage unit optimal operation can improve technical and economic performance indexes 52.41 and 23.55% respectively. In addition, demand response implementation can improve technical and economic performance indexes 10.76 and 21.95% respectively. Furthermore, demand response implementation and pumped-storage unit operation in case #4 improves technical and economic performance indexes 63.46 and 45.79% respectively. Therefore, although pumped-storage power plant has the better performance in comparison with demand response, the best results have been obtained in case #4 with both demand response and pumped-storage unit.

References

[1] World Energy Outlook 2015, Energy Access [Chapter 2], 2015.
[2] M.S. Ismail, M. Moghavvemi, T.M.I. Mahlia, Design of an optimized photovoltaic and microturbine hybrid power system for a remote small community case study of Palestine, Energy Convers. Manag. 75 (2013) 271–281.
[3] S.M.G. Mousavi, An autonomous hybrid energy system of wind/tidal/microturbine/battery storage, Electr. Power Energy Syst. 43 (2012) 1144–1154.
[4] E.S. Sreeraj, K. Chatterjee, S. Bandyopadhyay, Design of isolated renewable hybrid power systems, Sol. Energy 84 (2010) 1124–1136.
[5] R. Sebastián, J. Quesada, Distributed control system for frequency control in a isolated wind system, Renew. Energy 31 (2006) 285–305.
[6] S.F. Fux, M.J. Benz, L. Guzzella, Economic and environmental aspects of the component sizing for a stand-alone building energy system: a case study, Renew. Energy 55 (2013) 438–447.
[7] W. Alharbi, K. Raahemifar, Probabilistic coordination of microgrid energy resources operation considering uncertainties, Elec. Power Syst. Res. 128 (2015) 1–10.
[8] M.N. Ambia, A. Al-Durra, C. Caruana, S.M. Muyeen, Islanding operation of hybrid microgrids with high integration of wind driven cage induction generators, Sustain. Energy Technol. Assess. 13 (2016) 68–75.
[9] G. Prinsloo, A. Mammoli, R. Dobson, Discrete cogeneration optimization with storage capacity decision support for dynamic hybrid solar combined heat and power systems in isolated rural villages, Energy 116 (2016) 1051–1064.
[10] T.M. Hongxing, L.L. Yang, Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, Energy Convers. Manag. 79 (2014) 387–397.
[11] S. Conti, R. Nicolosi, S. Rizzo, H. Zeineldin, Optimal dispatching of distributed generators and storage systems for MV islanded microgrids, IEEE Trans. Power Deliv. 27 (2012) 1243–1251.
[12] A. Arabali, M. Ghofrani, M. Etezadi-Amoli, M.S. Fadali, Y. Baghzouz, Genetic-algorithm-based optimization approach for energy management, IEEE Trans. Power Deliv. 28 (January (1)) (2013) 162–170.
[13] S. Gottwalt, J. Gärttner, H. Schmeck, C. Weinhardt, Modeling and valuation of residential demand flexibility for renewable energy integration, IEEE Trans. Smart Grid 10 (March) (2016) 1–10.
[14] A. Mohseni, S.S. Mortazavi, A. Ghasemi, A. Nahavandi, M. Talaei abdi, The application of household appliances' flexibility by set of sequential uninterruptible energy phases model in the day-ahead planning of a residential microgrid, Energy 139 (2017) 315–328.
[15] K. Balasubramaniam, P. Saraf, R. Hadidia, E.B. Makram, Energy management system for enhanced resiliency of microgrids during islanded operation, Elec. Power Syst. Res. 137 (2016) 133–141.
[16] A. Ghasemi, S.S. Mortazavi, E. Mashhour, Hourly demand response and battery energy storage for imbalance reduction of smart distribution company embedded with electric vehicles and wind farms, Renew. Energy 85 (2016) 124–136.
[17] S.V. Papaefthymiou, E.G. Karamanou, S.A. Papathanassiou, M.P. Papadopoulos, Wind-hydro-pumped storage station leading to high RES Penetration in the autonomous island system of Ikaria, IEEE Trans. Sustain. Energy 1 (3) (2010) 163–172.
[18] T. Ma, H. Yang, L. Lu, Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, Energy Convers. Manag. 79 (2014) 387–397.
[19] LAZARD'S Levelized Cost of Storage-Version 2.0, 2016 (Online) Available at: https://www.lazard.com. (Accessed January 2018).
[20] T. Ma, H. Yang, L. Lu, Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, Energy Convers. Manag. 79 (2014) 387–397.
[21] M. Zhao, Z. Chen, F. Blaabjerg, Probabilistic capacity of a grid connected wind farm based on optimization method, Renew. Energy 31 (2006) 2171–2187.
[22] H.A. Aalami, S. Nojavan, Energy storage system and demand response program effects on stochastic energy procurement of large consumers considering renewable generation, IET Gener. Transm. Distrib. 10 (1) (2016) 107–114.
[23] Z.W. Zhenga, Y.Y. Chenb, M.M. Huoa, B. Zhaoc, An overview: the development of prediction technology of wind and photovoltaic power generation, Energy Proced. (12) (2011) 601–608.
[24] S. Rahimi, T. Niknam, F. Fallahi, A new approach based on benders decomposition for unit commitment problem, World Appl. Sci. J. 6 (12) (2009) 1665–1672.
[25] A. Safdarian, M. Fotuhi-Firuzabad, M. Lehtonen, Integration of price-based demand response in DisCos' short-term decision model, IEEE Trans. Smart Grid 5 (5) (2014) 2235–2245.
[26] M. Doostizadeh, H. Ghasemi, A day-ahead electricity pricing model based on smart metering and demand-side management, Energy 46 (2012) 221–230.
[27] FERC, Staff Report, Assessment of Demand Response and Advanced Metering, Aug. 2012 (Online). Available at: http://www.FERC.gov. (Accessed January 2018).
[28] U. Nasir, Z. Iqbal, M.T. Rasheed, H. Minxiao, Active and Reactive Power Control of a Variable Speed Pumped Storage System, Environment and Electrical Engineering (EEEIC), Rome, 2015, pp. 6–14.
[29] H.A. Aalami, M. Parsa Moghaddam, G.R. Yousefi, Modeling and prioritizing demand response programs in power markets, Elec. Power Syst. Res. 80 (2010) 426–435.
[30] GAMS Webpage: http://www.gams.com; [Accessed January 2018].