Chapter 9
Multi-Objective Optimization Model for Optimal Performance of an Off-Grid Microgrid with Distributed Generation Units in the Presence of Demand Response Program

Afshin Najafi-Ghalelou, Kazem Zare, Sayyad Nojavan, and Mehdi Abapour

Nomenclature

Sets

t Time period

Parameters

$C_{\text{Batt, Ch}}$, $C_{\text{Batt, Dch}}$	Charging and discharging costs of the battery
C_{Ue}, C_{Exe}	Cost of undelivered energy and excess generated energy
C_{WT}, C_{PV}, C_{FC}	Cost of produced power by the wind turbine, photovoltaic panel, and fuel cell unit
$E^{\max}$	Maximum allowed shifted load in the DRP
L_t	Electricity demand
$P_t^{\text{Batt,limit}}$	Limitation of stored energy in the battery
$P_t^{\text{Batt,dch,limit}}$, $P_t^{\text{Batt,ch,limit}}$	Discharging and charging limitations of the battery
$P_t^{\text{WT,limit}}$, $P_t^{\text{PV,limit}}$, $P_t^{\text{FC,limit}}$	Limitation of produced power by the wind turbine, photovoltaic panel, and fuel cell unit

A. Najafi-Ghalelou · K. Zare (✉) · M. Abapour
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
e-mail: afshin.najafi95@ms.tabrizu.ac.ir; kazem.zare@tabrizu.ac.ir; abapour@tabrizu.ac.ir

S. Nojavan
Department of Electrical Engineering, University of Bonab, Bonab, Iran
e-mail: sayyad.nojavan@bonabu.ac.ir

Variables

Exe_t	Excess generated power
L_t^{New}	New electricity demand after implementation of DRP
$L_t^{\mathrm{shiftable}}$	Amount of shifted load by DRP
P_t^{Batt}	State of charge of the battery
$P_t^{\mathrm{Batt,ch}}$, $P_t^{\mathrm{Batt,dch}}$	Charging and discharging power of the battery
P_t^{WT}, P_t^{PV}, P_t^{FC}	Produced power by the wind turbine, photovoltaic panel, and fuel cell unit
Ue_t	Undelivered energy
X_t	Binary variable: Equal to 1 if the battery be in charging mode, otherwise 0
Y_t	Binary variable: Equal to 1 if the battery be in discharging mode, otherwise 0

9.1 Introduction

Recently, some new concepts such as microgrid have been appeared with the aim of handling various issues related to integration of renewable energy sources and increased demand of reliable electricity supply. So, some studies should be done not only to make such concepts technically feasible but also to be commercially attractive and viable.

9.1.1 Literature Review

Literature review about deterministic-based model of microgrid energy management has been provided as follows: to fairly distribute the bill costs among buildings, a novel residential microgrid model has been provided in [1]. Total operation cost of a residential microgrid has been minimized in the presence of solar thermal storage system in [2]. Performance of an islanded microgrid has been optimized in [3] which consists of wind turbine, photovoltaic panel, fuel cell, and battery. Compressed air energy storage-based model of a microgrid has been optimized under various uncertainties in [4].

Literature review about uncertainty-based model of microgrid energy management has been provided as follows: A novel robust load frequency control strategy has been provided in [5] for analyzing the operation of the islanded microgrid considering vehicle-to-grid constraints. Information gap decision theory approach-based model of a residential microgrid has been analyzed under market price uncertainty in [6]. The particle swarm optimization algorithm has been presented in [7] to optimize the microgrid performance in a real-time operation mode. Solar thermal storage-based model of a residential microgrid has been analyzed under

market price uncertainty in [8]. In order to investigate the charging effects of plug-in hybrid electric vehicles on the optimal operation of microgrid, a novel stochastic approach has been provided in [9]. Robust optimization approach has been utilized in [10] to minimize the operation cost of a compressed air energy storage-based microgrid under market price uncertainty. ROA-based residential model has been optimized under market price uncertainty in [11]. With the aim of optimizing the microgrid's operation cost in the presence of renewable energy sources, an additive and integrated net load forecast model has been presented in [12]. Short-term risk-based model of a smart residential microgrid has been analyzed under market price uncertainty in [13]. Market price uncertainty-based model of a hub system has been optimized using robust optimization approach in [14]. A genetic algorithm-based model of the hydrothermal model has been optimized in [15]. A novel robust optimization approach-based model of a novel microgrid has been studied under market price uncertainty in [16].

Literature review about microgrid energy management considering various objective functions has been provided as follows: with the aim of decreasing the operation cost and emission of microgrid, a multi-objective uniform water cycle approach has been provided in [17]. A renewable energy-based microgrid model has been studied from economic and environmental viewpoints considering compressed energy storage system and demand response program in [18]. A multi-objective framework has been presented in [19] to minimize the emission and the cost of a microgrid using normal boundary intersection technique. In order to mitigate the fluctuation of power flow, decrease energy cost, and reduce the emission of green-house gases, a novel multi-objective-based model of microgrid has been provided in [20]. A ε-constraint approach has been used in [21] for optimal scheduling of a novel hybrid energy system under economic and environmental factors. A multi-objective-based cost-emission model of a residential apartment building has been optimized using ε-constraint and weighted sum approaches in [22]. Finally, a multi-objective-based cost-emission model of a hybrid system is optimized utilizing weighted sum approach in [23].

9.1.2 Novelty of This Chapter

1. Minimizing the operation and energy not supplied costs at the same time under DRP constraints.
2. Using ε-constraint and fuzzy satisfying approaches to solve the proposed multi-objective problem and select the best compromise solution.

9.1.3 Chapter Organization

The chapter is structured as follows: The proposed multi-objective optimization model is formulated in Sect. 9.2. In Sect. 9.3, two different scenarios have been investigated with and without considering the effects of DRP. Finally, the conclusion is presented in Sect. 9.4.

9.2 Problem Formulation

9.2.1 Objective Function 1

The first objective function of the proposed chapter is minimization of the microgrid's operation cost:

$$
\begin{aligned}
Min\,OF_1 = \sum_{t=1}^{24} \big(& P_t^{WT} \times C_{WT} + P_t^{PV} \times C_{PV} + P_t^{FC} \\
& \times C_{FC} - P_t^{Batt,ch} \times C_{Batt,Ch} + P_t^{Batt,dch} \times C_{Batt,Dch} \big) \quad (9.1)
\end{aligned}
$$

The first term of the proposed objective function (9.1) is related to the cost of produced power by the wind turbine. The second and third terms are related to the cost of produced power by the photovoltaic panel and the fuel cell unit. The cost of consumed power with the aim of charging the battery is presented in the fourth term. Finally, the cost of produced power through the discharge process of the battery is provided in the last term.

9.2.2 Objective Function 2

The second objective function is presented to minimize the energy not supplied cost in the microgrid.

$$
Min\,OF_2 = \sum_{t=1}^{24} (Ue_t \times C_{Ue}) \qquad (9.2)
$$

9.2.3   Constraints of the Wind Turbine, Photovoltaic Panel, and Fuel Cell

Produced power by the wind turbine, photovoltaic panel, and fuel cell are provided as follows:

$$P_t^{\text{WT}} \leq P_t^{\text{WT,limit}} \tag{9.3}$$

$$P_t^{\text{PV}} \leq P_t^{\text{PV,limit}} \tag{9.4}$$

$$P_t^{\text{FC}} \leq P_t^{\text{FC,limit}} \tag{9.5}$$

9.2.4   Constraints of the Battery

The technical constraints of the battery are formulated by Eqs. (9.6)–(9.12) [3]. The state of charge, charge and discharge limitations of the battery are expressed by Eqs. (9.6)–(9.8).

$$P_t^{\text{Batt}} \leq P_t^{\text{Batt,limit}} \tag{9.6}$$

$$P_t^{\text{Batt,dch}} \leq P_t^{\text{Batt,dch,limit}} \times X_t \tag{9.7}$$

$$P_t^{\text{Batt,ch}} \leq P_t^{\text{Batt,ch,limit}} \times Y_t \tag{9.8}$$

Equation (9.9) is presented to control the charge and discharge mode of the battery.

$$X_t + Y_t = 1 \tag{9.9}$$

Maximum limits of discharging and charging of the battery are presented in Eqs. (9.10) and (9.11), respectively.

$$P_t^{\text{Batt,dch}} - P_{t-1}^{\text{Batt}} \leq 0 \tag{9.10}$$

$$P_t^{\text{Batt,ch}} + P_{t-1}^{\text{Batt}} \leq P_t^{\text{Batt,limit}} \tag{9.11}$$

Finally, Eq. (9.12) is presented to update the state of charge of battery.

$$P_t^{\text{Batt}} = P_{t-1}^{\text{Batt}} + P_t^{\text{Batt,ch}} - P_t^{\text{Batt,dch}} \tag{9.12}$$

9.2.5 Demand Response Program

The time-of-use (TOU) rates of demand response program are used in the chapter. TOU shifts the electricity demand from peak periods to flatten the load curve, improve the performance of microgrid, and decrease the operation cost of the microgrid. The utilized DRP can be formulated as follows:

$$L_t^{\text{New}} = L_t + L_t^{\text{shiftable}} \tag{9.13}$$

$$\left| L_t^{\text{shiftable}} \right| \leq E^{\max} \times L_t \tag{9.14}$$

$$\sum_{t=1}^{T} L_t^{\text{shiftable}} = 0 \tag{9.15}$$

It is noteworthy that it is assumed only 20% of the base load can be shifted at each period.

9.2.6 Power Balance Constraints

Power balance limitation can be formulated as follows:

$$P_t^{\text{WT}} + P_t^{\text{PV}} + P_t^{\text{FC}} + P_t^{\text{Batt,dch}} + \text{Ue}_t = L_t + P_t^{\text{Batt,ch}} + \text{Exe}_t \tag{9.16}$$
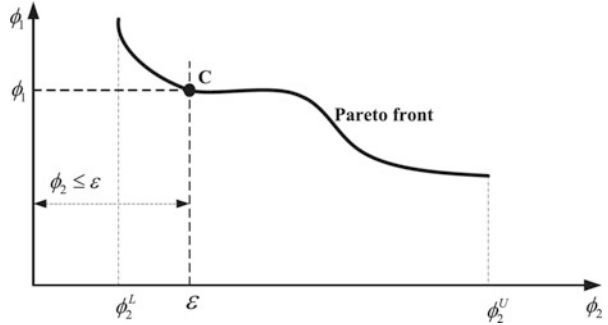
It should be mentioned that on the right side of Eq. (9.16), L_t^{New} should be replaced with L_t to consider the effects of the proposed DRP.

9.2.7 ε-Constraint Method

In this chapter, the proposed multi-objective optimization model is solved using the ε-constraint method. In order to create Pareto front, objective function (9.1) is minimized, while the second objective function is considered as a constraint. The mathematical formulation of mentioned statements can be expressed as follows [24]:

$$\text{OF} = \max\left(\Phi_1\right)$$
$$\text{s.t.}$$
$$\begin{cases} \Phi_2 \leq \varepsilon \\ \text{Eqs.}(9.3) - (9.20) \end{cases} \tag{9.17}$$

Fig. 9.1 Description of ε-constraint method

It can be observed from the Eq. (9.17) and Fig. 9.1 that the ε is limited by Φ_2. In this section, by increasing ε from Φ_2^L to Φ_2^U, the modified single objective function is solved. With comparing the obtained results for each value of ε, the optimal solutions like point C in Fig. 9.1 are obtained.

9.2.8 Fuzzy Satisfying Method

Min-max fuzzy method is one of the best methods for selecting the optimal solution from the obtained Pareto solutions. The linear membership function can be described as follows:

$$\mu_k^n = \begin{cases} 1 & f_k^n \leq f_k^{\min} \\ \dfrac{f_k^{\max} - f_k^n}{f_k^{\max} - f_k^{\min}} & f_k^{\min} \leq f_k^n \leq f_k^{\max} \\ 0 & f_k^n \geq f_k^{\max} \end{cases} \tag{9.18}$$

In this equation, f_k^n is limited with minimum and maximum values of the kth objective function in Pareto optimal set. μ_k^n shows the optimality degree of nth solution of kth objective function. It should be mentioned that nth solution can be calculated as follows:

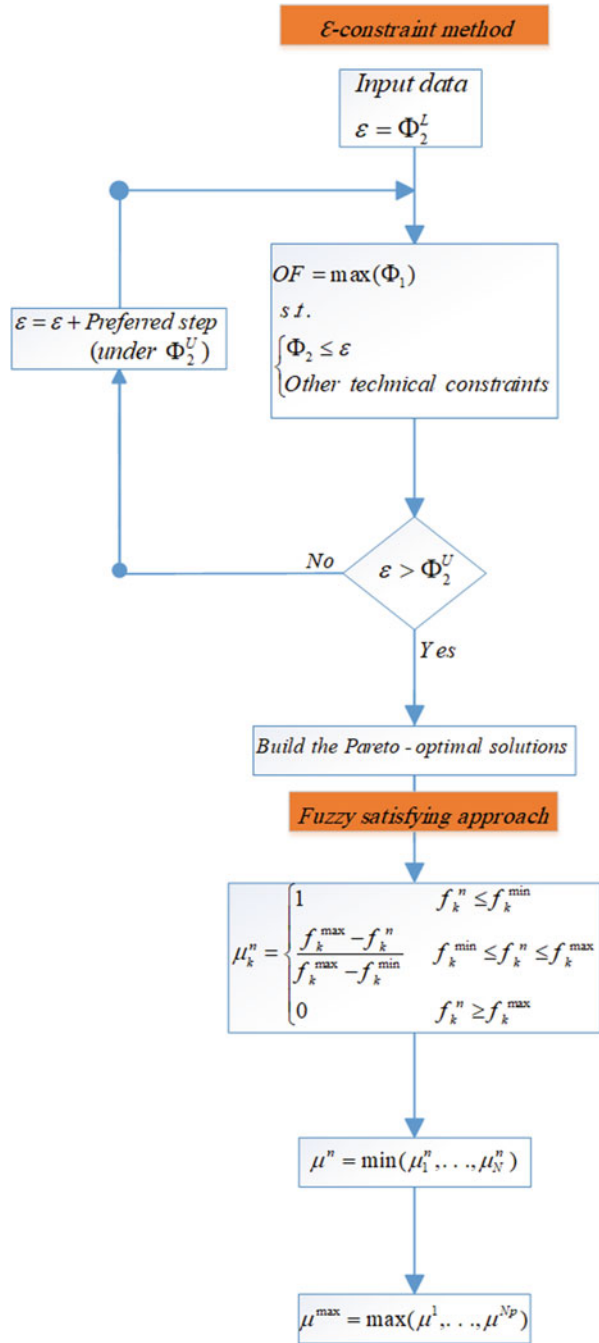$$\mu^n = \min\left(\mu_1^n, \ldots, \mu_N^n\right)$$
$$n = 1, \ldots, N_P \tag{9.19}$$

The maximum weakest membership function can be considered as the best strategy. Thus, the corresponding membership of solution ($\mu^{\max}$) can be calculated as follows:

$$\mu^{\max} = \max\left(\mu^1, \ldots, \mu^{N_P}\right) \tag{9.20}$$

The general flow chart of the utilized approaches is illustrated in Fig. 9.2.

Fig. 9.2 Flow chart of the
ε-constraint and min-max
fuzzy approaches

$\mathcal{E}$-constraint method

Input data

$\varepsilon = \Phi_2^L$

$OF = \max(\Phi_1)$

$s.t.$

$\begin{cases} \Phi_2 \leq \varepsilon \\ Other \ technical \ constraints \end{cases}$

$\varepsilon = \varepsilon + Preferred \ step$
$(under \ \Phi_2^U)$

No $\varepsilon > \Phi_2^U$

Yes

Build the Pareto - optimal solutions

Fuzzy satisfying approach

$$\mu_k^n = \begin{cases} 1 & f_k^n \leq f_k^{min} \\ \dfrac{f_k^{max} - f_k^n}{f_k^{max} - f_k^{min}} & f_k^{min} \leq f_k^n \leq f_k^{max} \\ 0 & f_k^n \geq f_k^{max} \end{cases}$$

$$\mu^n = \min(\mu_1^n, \ldots, \mu_N^n)$$

$$\mu^{max} = \max(\mu^1, \ldots, \mu^{Np})$$

9.3   Numerical Simulation

In the proposed chapter, an isolated microgrid in the Budapest Tech [25] is evaluated as a case study. As shown in Fig. 9.3, the proposed sample microgrid comprises of renewable energy sources such as wind turbine, photovoltaic panel, fuel cell, and battery storage.

9.3.1   Input Data

The types of used wind turbine, photovoltaic panel, and fuel cell are "Air-X 401," "DS 40," and "Flexiva" with the nominal power of 400 W at 11.5 m/s, 40 W, and 80 W, respectively. The output of the wind turbine and photovoltaic panel are provided in Figs. 9.4 and 9.5, respectively. Also, the estimated load profile is illustrated in Fig. 9.6. Notably the optimization problem is investigated under two load profiles. Parameters related to the costs of different units and their relevant limitations are presented in Table 9.1.

9.3.2   Simulation Results in Two Study Cases

In this chapter, two case studies are analyzed with the aim of evaluating the performance of the proposed model. The proposed model without considering the

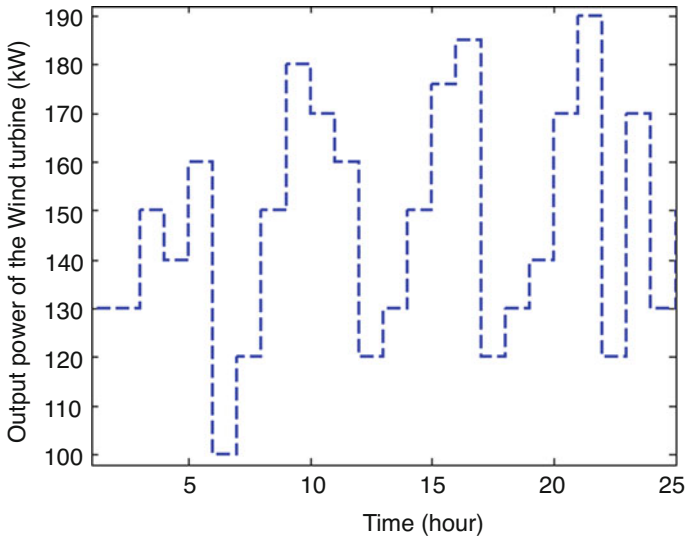**Fig. 9.3** Schematic of the proposed microgrid model
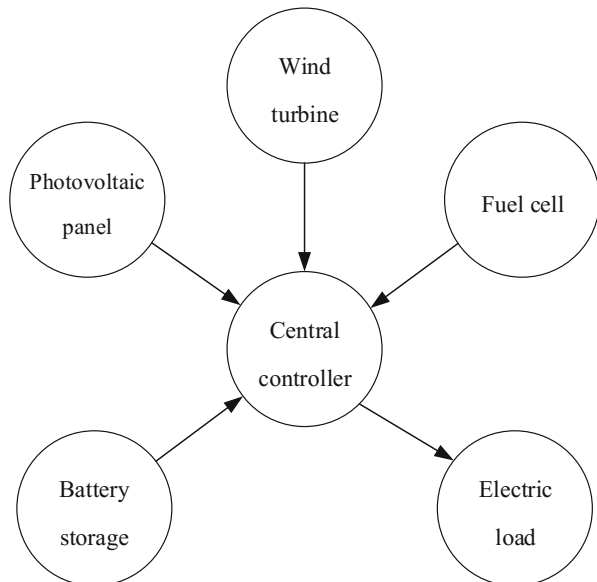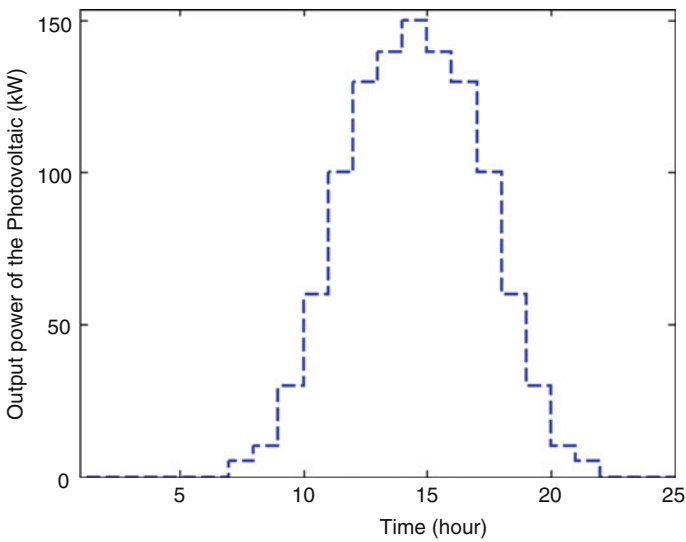
Fig. 9.4 Output power of wind turbine

Fig. 9.5 Output power of photovoltaic system

DRP constraints has been analyzed in the first scenario and with considering the DRP constraints has been investigated in the second one.

The state of charge of battery and the charge and discharge rates of battery are illustrated in Figs. 9.7 and 9.8, respectively.
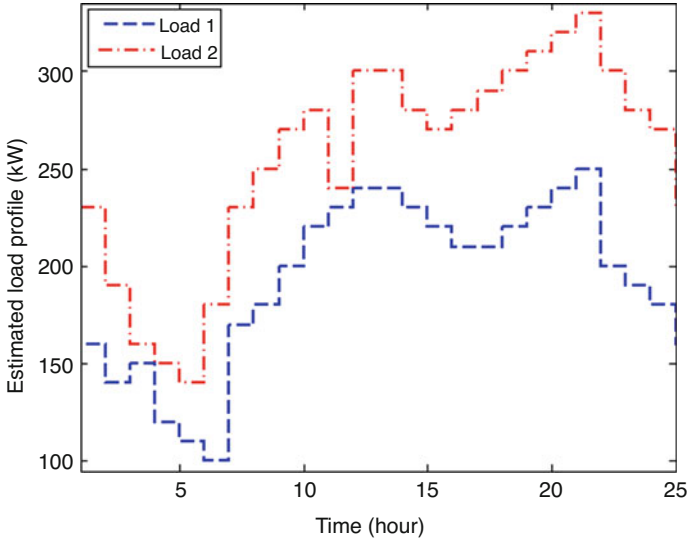
Fig. 9.6 Load profiles

Table 9.1 Costs of different units and their relevant limitations

Parameter	Unit	Value	Parameter	Unit	Value
C_{WT}	€/kWh	0.4	$P_t^{FC,limit}$	W	80
C_{PV}	€/kWh	0.4	$P_t^{Batt,limit}$	W	200
C_{FC}	€/kWh	0.9	$P_t^{Batt,dch,limit}$	W	50
$C_{Batt,\ Ch}$	€/kWh	0.4	$P_t^{Batt,ch,limit}$	W	200
$C_{Batt,\ Dch}$	€/kWh	0.6			
C_{Ue}	€/kWh	1.5			
C_{Exe}	€/kWh	Free			

By analyzing these two figures, it can be understood that without DRP, the state of charge of battery is 1995 kWh. Meanwhile, with considering the DRP, the state of charge of battery is 3423.56 kWh, and this means that with considering DRP, the state of charge of battery increases 1428.5644 kWh. Also amount of charge without DRP is 175 kWh and with DRP is 167 kWh, which means that the charge of battery decreases 8 kWh under the DRP. Furthermore, discharge rate without DRP is 275 kWh and with DRP is 98.36 kWh. So, the discharge rate of battery decreases 176.64 kW under the DRP. In general, it can be concluded that with considering the DRP, the charge and discharge rates of battery are decreased which makes the battery life to be increased and the operation cost of microgrid decreased.

The excess energy is illustrated in Fig. 9.9. According to the provided figure, it can be understood that without DRP, the excess energy is 266 kWh and with DRP is zero. Thus, the excess energy decreases 266 kWh and becomes zero under the DRP. In general, reduction of excess energy decreases the operation cost of the microgrid.
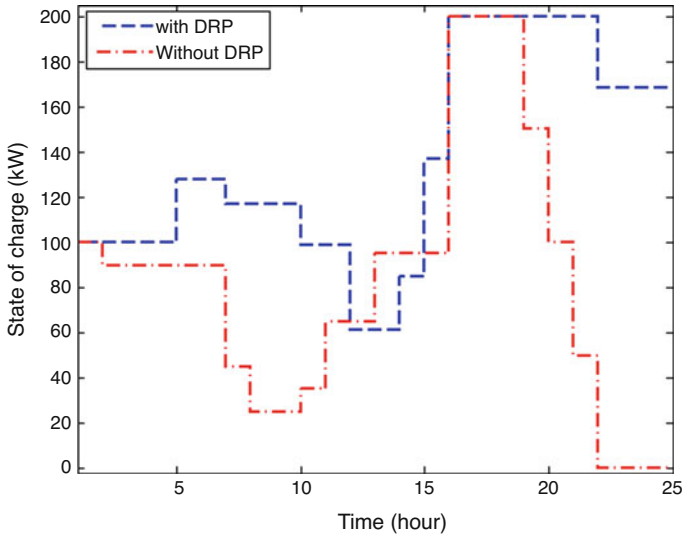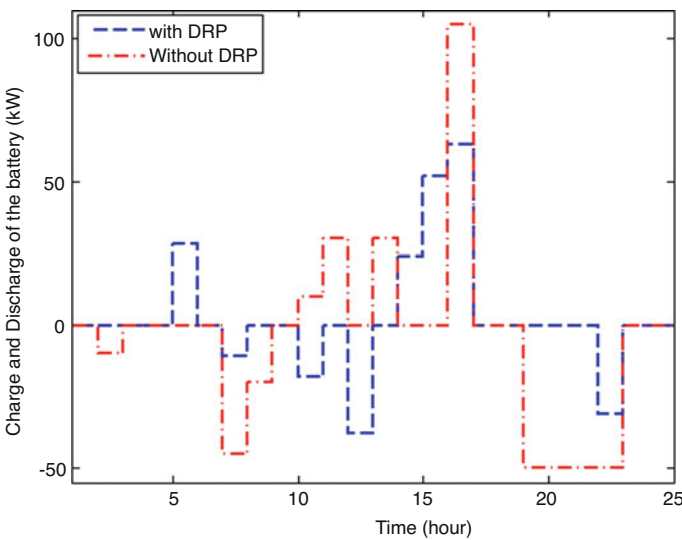
Fig. 9.7 State of charge of battery

Fig. 9.8 Charge and discharge of battery

The energy not supplied is provided in Fig. 9.10. According to this figure, without considering DRP the undelivered energy is 163.017 kWh and with considering DRP is 67.64 kWh, which means that with considering DRP the undelivered energy decreases 95.377 kWh and this leads to the reduction of the operation cost. It should be mentioned that the output power of fuel cell without DRP is 1.98 kWh and with DRP is zero, and this low output power is due to high operation cost of the fuel cell.
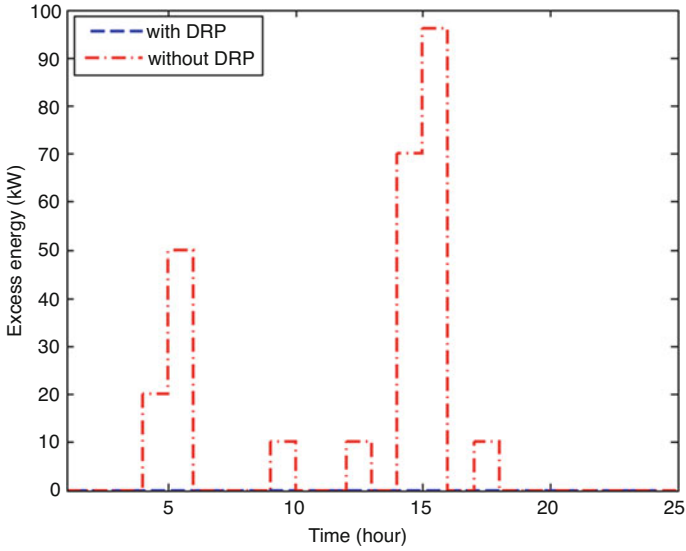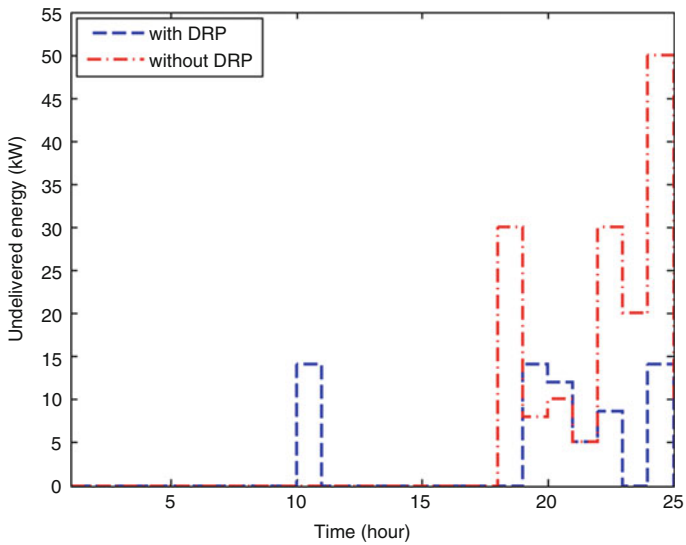
Fig. 9.9 Excess energy

Fig. 9.10 Undelivered energy

Finally, the obtained Pareto solutions with and without DRP are summarized in Table 9.2. In the first scenario, by using min-max fuzzy method, solution#19 is selected as the trade-off solution in which the operation cost of microgrid is

Table 9.2 Pareto solutions with and without considering DRP

	Without demand response program					With demand response program				
	Operation cost (€)	Energy not supplied cost (€)	Φ_1 (p.u.)	Φ_2 (p.u.)	min (Φ_1, Φ_2)	Operation cost (€)	Energy not supplied cost (€)	Φ_1	Φ_2	min (Φ_1, Φ_2)
1	2252.400	0	0	1.000	0	1889.200	0	0	1.000	0
2	2098.518	2.304	0.353	0.997	0.353	1864.010	62.976	0.353	0.736	0.353
3	2089.969	16.552	0.373	0.980	0.373	1862.610	66.475	0.373	0.721	0.373
4	2081.420	30.801	0.392	0.962	0.392	1861.211	69.974	0.392	0.706	0.392
5	2072.871	45.049	0.412	0.944	0.412	1859.811	73.472	0.412	0.692	0.412
6	2064.322	59.297	0.431	0.927	0.431	1858.412	76.971	0.431	0.677	0.431
7	2055.773	73.546	0.451	0.909	0.451	1857.012	80.470	0.451	0.662	0.451
8	2047.224	87.794	0.471	0.892	0.471	1855.613	83.968	0.471	0.648	0.471
9	2038.675	102.042	0.490	0.874	0.490	1854.213	87.467	0.490	0.633	0.490
10	2030.125	116.291	0.510	0.856	0.510	1852.814	90.966	0.510	0.618	0.510
11	2021.576	130.539	0.529	0.839	0.529	1851.414	94.464	0.529	0.604	0.529
12	2013.027	144.788	0.549	0.821	0.549	1850.015	97.963	0.549	0.589	0.549
13	2004.478	159.036	0.569	0.804	0.569	**1848.615**	**101.462**	**0.569**	**0.574**	**0.569**
14	1995.929	173.284	0.588	0.786	0.588	1847.216	104.960	0.588	0.560	0.560
15	1987.380	187.533	0.608	0.768	0.608	1845.816	108.459	0.608	0.545	0.545
16	1978.831	201.781	0.627	0.751	0.627	1844.417	111.958	0.627	0.530	0.530
17	1970.282	216.029	0.647	0.733	0.647	1843.017	115.456	0.647	0.515	0.515
18	1961.733	230.278	0.667	0.716	0.667	1841.618	118.955	0.667	0.501	0.501
19	**1953.184**	**244.526**	**0.686**	**0.698**	**0.686**	1840.219	122.454	0.686	0.486	0.486
20	1944.635	264.412	0.706	0.674	0.674	1838.819	125.952	0.706	0.471	0.471
21	1936.086	285.784	0.725	0.647	0.647	1837.420	129.451	0.725	0.457	0.457
22	1927.537	307.157	0.745	0.621	0.621	1836.020	132.950	0.745	0.442	0.442
23	1918.988	328.529	0.765	0.594	0.594	1834.621	136.448	0.765	0.427	0.427
24	1910.439	349.902	0.784	0.568	0.568	1833.221	139.947	0.784	0.413	0.413

25	1901.890	371.275	0.804	0.542	0.542	1831.822	143.446	0.804	0.398	0.398
26	1893.341	392.647	0.824	0.515	0.515	1830.422	146.944	0.824	0.383	0.383
27	1884.792	414.020	0.843	0.489	0.489	1829.023	154.329	0.843	0.352	0.352
28	1876.243	435.392	0.863	0.462	0.462	1827.623	164.825	0.863	0.308	0.308
29	1867.694	456.765	0.882	0.436	0.436	1826.224	175.321	0.882	0.264	0.264
30	1859.145	478.137	0.902	0.410	0.410	1824.824	185.817	0.902	0.220	0.220
31	1850.596	499.510	0.922	0.383	0.383	1823.425	196.313	0.922	0.176	0.176
32	1842.047	520.882	0.941	0.357	0.357	1822.025	206.809	0.941	0.132	0.132
33	1833.498	542.255	0.961	0.331	0.331	1820.626	217.305	0.961	0.088	0.088
34	1824.949	595.882	0.980	0.264	0.264	1819.226	227.801	0.980	0.044	0.044
35	1820.400	810.000	1.000	0	0	1817.827	238.294	1.000	0	0

1953.184 € and the unsupplied energy cost is 244.526 €. In the second scenario, solution#13 is selected as the trade-off solution in which the operation cost of microgrid is 1848.615 € and unsupplied energy cost is 101.462 €. Consequently, the operation cost of the microgrid increases 5.36% and the cost of unsupplied energy reduces 58.51% under the DRP.

9.4   Conclusion

In this chapter, two conflicted objective functions of an off-grid microgrid, operation cost and energy not supplied, have been provided. To handle the provided multi-objective model, ε-constraint method is used. Then, fuzzy satisfying approach is employed to select the best compromise solution from the obtained solutions. According to the obtained results, the operation cost of microgrid is increased 5.36% and the cost of unsupplied energy is reduced 58.51% in the presence of DRP. So, it can be concluded that DRP can be employed to provide desired economic ideals. It should be noted that some new multi-microgrid models can be analyzed under various conditions as a future work.

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