A Two-stage Optimization Method for Economic Operation of the Micro-grid

Hua Shao, Chunguang He, Jiakun An, Wenyuan Han, Guangxin Zhai

Abstract:

In this paper, a two-stage optimization method is presented to achieve the goal of economic operation of the Micro-grid. The first stage minimizes the user cost on the basis of load scheduling, taking users' satisfaction into consideration and the model is solved by Particle Swarm Optimization (PSO) algorithm. The second level is aimed at optimizing output of units including a wind turbine, a photovoltaic, a battery storage system and a micro-turbine in micro-grid. The economic operational cost is considered in micro-grid model, which is solved by mixed integer linear programming method. In the test case, operational costs in two scenarios including load characteristic and without load characteristic are separately analyzed, and the output of units are compared. The results show that based on the proposed two-stage optimization method, the operation cost of micro-grid will be reduced obviously.

Keywords:

Micro-grid; Two-stage Optimization; Economic Dispatch; Renewable energy

1. Introduction

Micro-grid (MG) represents a new way to utilize renewable energy for future smart grid [1]. The grid does not necessary to be faced with a variety of DGs because of MG. And the key technologies of micro-grid operation and energy management can reduce the harmful impacts brought to the distributed network by intermittent characteristics of DGs. Meanwhile, micro-grid can take full advantage of the output of DGs to improve the economic performance.

Many publications are aimed at the operation of micro-grid and the optimization of DGs [2-10]. An optimization procedure that enables the optimal dispatching of distributed generators and storage systems in a medium-voltage islanded micro-grid is presented in [2]. A two-stage optimal method of micro-grid system that combines cool, heat and power (CCHP) is presented in [3]. A smart energy management system (SEMS), which consists of power forecast module, energy storage system (ESS), management module and optimization module to optimize the operation of the micro-grid [4]. A business model is proposed to operate the community based on the multi-micro-grids, which involves critical loads and generators of multiple owners [5]. A novel battery operation cost model is proposed which considers a battery as an equivalent fuel-run generator to enable it to be incorporated into a unit commitment problem in [6]. An information exchange framework to incorporate smart building demands into a micro-grid operation is proposed in [7]. A stochastic operation scheduling scheme is proposed to co-optimize carbon emissions and generation fuel costs in [8]. The load scheduling on user side has also been investigated [11-16]. [11] introduces a novel concept of cost efficiency-based residential load scheduling framework to improve the economical efficiency of the residential electricity consumption. [12] focuses on the problems of load scheduling and power trading in systems with high penetration of renewable energy resources (RERs) and adopts approximate dynamic programming to schedule the operation of different types of appliances including must-run and controllable appliances. A demand response aggregator (DRA)-coordinated load scheduling in distribution system with responsive loads is presented in [13]. Actually, the loads in micro-grid can be divided into non-interruptible load, transferrable load and interruptible load. The optimization of loads in user side will improve the economic operation of micro-grid.

In this work, a two-stage optimal model for the economic operation of micro-grid considering into the load characteristics in the user side is presented. The first stage takes user satisfaction into account and the second stage aims at the units' output in micro-grid to reduce the operational cost of micro-grid. The results show that the economic operation of micro-grid will improve.

In the sections that follow, this paper first clarifies the architecture of micro-grid and the two-stage method in section II. Section III presents the first-stage model and method considering load scheduling, what's more, the second-stage model for economic operation of micro-grid and mixed integer programming method is applied to solve the model. A test case shows the economic operation of micro-grid under two different scenarios in section IV. Finally, the conclusions are summarized.

2. Two-stage optimization model

The basic structure of the Mciro-grid contains: Wind Turbine (WT), Micro Turbine (WT), Photovoltaic (PV) and the Battery Energy Storage System (BESS). the micro-grid is connected to the

---

This work is supported by the National Natural Science Foundation of Hebei Province (E2016203278)

Hua Shao, is with the Economic and Technology Research Institute, State Grid Hebei Electric Power Company Shijiazhuang, Hebei, China(+86-13910770613, hebeishaohua2017@163.com),

distributed network through the common coupling(PCC).

In the two-stage optimization model, the first stage is focus on the load scheduling for the user side, which gives guidelines of load scheduling strategy on the basis of time-of-use(TOU) price. The second stage is concentrated on the economic operation in the power side of micro-grid, which is to develop strategies of operation by optimizing the units. Fig.1 shows the main optimization architecture.

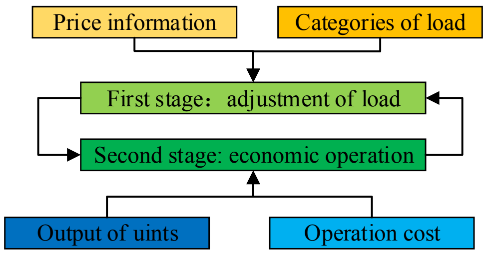

Figure 1. Architecture diagram of two-stage optimization

3. The First-stage Model and Method

The first stage model is mainly about load adjustment and solved by particle swarm optimization (PSO) algorithm. This paper first presents the load scheduling model considering the user satisfaction. Then the corresponding solution method is given as bellow.

3.1 Objective Function

This paper carries on load scheduling based on TOU and user satisfaction. The objective function is expressed as:

$$\min C=\sum_{t=1}^{N}p(t)l(t)+\sum_{t=1}^{N}s(l(t),d(t)) \tag{1}$$

where N is the total number of time interval in an operation cycle, $p(t)$ and $l(t)$ are the price and adjusted load in time steps t, $d(t)$ is the load before adjustment. C is the total cost in micro-grid. And s is the user's satisfaction function, which can be expressed as:

$$s(l,d)=-d(t)\frac{\alpha(t)\beta(t)}{1+\alpha(t)}[(\frac{l(t)}{d(t)})^{\frac{1+\alpha(t)}{\alpha(t)}}-1] \tag{2}$$

where $\alpha<0$ and $\beta>0$, and the two parameters are related to price, as shown in [17].

3.2 Constraint Conditions

Firstly, the total load before adjustment and the actual load after adjustment for an operation cycle are the same:

$$\sum_{t=1}^{N}l(t)=\sum_{t=1}^{N}d(t) \tag{3}$$

Then, the minimum load demand of users need to be met in every time steps *t*, it can be easily known that the load demand is less than upper bound and maximum power generated by micro-grid:

$$l_{un}(t)\le l(t)\le \min(l_{\max}(t),g_{\max}(t)) \tag{4}$$

where $l_{un}(t)$, $l_{\max}(t)$ is the non-interrupted load and its upper limit, and $g_{\max}(t)$ is the maximum generation in micro-grid.

3.3 PSO Algorithm

Particle swarm optimization (PSO) has many advantages, such as its simple concept, few parameters, fast convergence speed and strong robustness, so it is widely applied to solve optimization problems in power systems. The above model is a nonlinear programming problem, therefore it can be solved by PSO. The flow chart is shown in Fig.2.

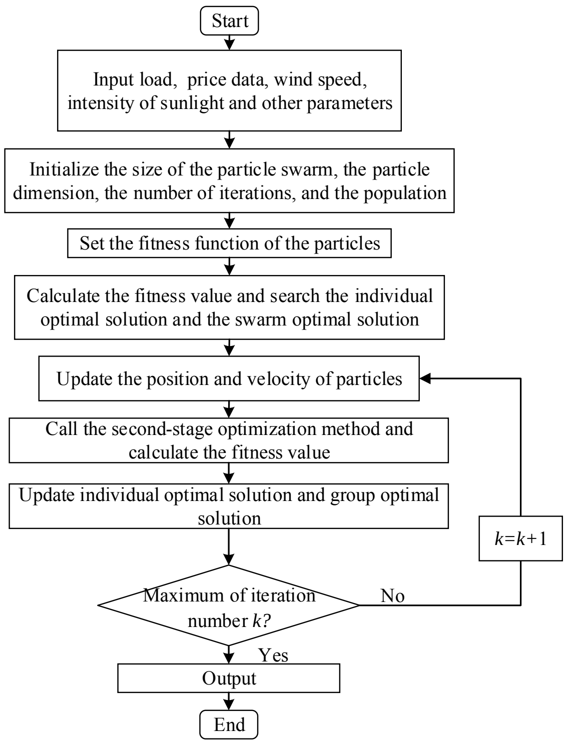

Figure 2. Flow chart of upper optimal model solution

4. The Second-stage Model and Method

This section starts with mathematical models of units in micro-grid. Then the optimization model and corresponding solution method are presented.

4.1 Models of Units in Micro-grid

Units of micro-grid are mainly BESS, PV, WT, and MT. This paper first introduces output model of PV and WT. PV's output can be expressed as:

$$P_{PV} = P_{STC}\frac{G_T}{G_{STC}}[1-k(T_c-T_\tau)] \quad (5)$$

In (5), P_{STC} is the maximum power under standard experiment condition(incident intensity of sunlight G_{STC} is equal to 1000W/m^2 and ambient temperature T_τ is equal to 25℃), G_T is the light intensity of PV, k is power temperature coefficient, which is usually 0.47%/℃, T_c is temperature of PV.

WT's output is tightly determined by wind speed:

$$P_{WT} = \begin{cases} 0 & 0 \le v < v_{ci} \\ \mathrm{A}v^3+\mathrm{B}v^2+\mathrm{C}v+D & v_{ci} \le v < v_r \\ P_r & v_r \le v < v_{co} \\ 0 & v_{co} < v \end{cases} \quad (6)$$

In (6), P_r and v are rated power of WT and wind speed, v_{ci}, v_{co} and v_r are cut-in speed, cut-out speed and rated speed of WT, and *A*, *B*, *C* and *D* are fixed parameters of WT.

Charging power $P_{ch}(t)$ and discharging power of BESS $P_{dis}(t)$ are bound to its state of charge(SOC). *SOC* of charging and discharging are determined by equations (7):

$$\begin{cases} SOC(t) = SOC(t-1) + P_{ch}(t)\Delta t\eta_{ch} / E \\ SOC(t) = SOC(t-1) + P_{dis}(t)\Delta t / (E\eta_{dis}) \end{cases} \quad (7)$$

Where η_{ch} and η_{dis} are charging and discharging efficiency of BESS, Δt is its charging or discharging interval, and E is its rated capacity.

Therefore, the output of BESS $P_B(t)$ is expressed as:

$$P_B(t) = P_{dis}(t) - P_{ch}(t) \quad (8)$$

The positive or negative value of $P_B(t)$ indicates that BESS is discharging or not.

Then, take the *C65* type Micro-turbine produced by *Capstone* as an example. The output P_{MT} is related to its generation efficiency η_{MT}, which can be expressed as:

$$\eta_{MT}(t) = 0.0753(\frac{P_{MT}(t)}{65})^3 - 0.3095(\frac{P_{MT}(t)}{65})^2 + 0.4174(\frac{P_{MT}(t)}{65}) + 0.1068 \quad (9)$$

4.2 Objective Function

In this paper, the optimization model of operational cost in a cycle is performed. The operational cost C_o consists of fuel cost, C_{MT}, electricity purchasing cost C_p, operation and maintenance cost C_m and environmental cost C_e, which can be expressed as follows:

$$\begin{cases} \min C_o = \sum_{t=1}^{N}[C_{MT}(t) + C_p(t) + C_m(t) + C_e(t)] \\ C_{MT}(t) = \frac{C_n P_{MT}(t)}{\eta_{MT}(t)L} \\ C_p(t) = p(t)P_t(t) \\ C_m(t) = \sum_{i=1}^{N_e} K_i P_i(t) \\ C_e(t) = \sum_{i=1}^{N_e}\sum_{j=1}^{N_p} \mu_j \omega_{ij} P_i(t) \end{cases} \quad (10)$$

Where, C_n is the price of gas per cubic meter and the value is based on China gas cost, which is equal to 0.363\$/m^3 (The RMB has been converted into dollars), L is low calorific value per cubic meter of natural gas and it is an invariant constant, which is 9.7, $P_t(t)$ is the exchange power between micro-grid and distributed network, $P_i(t)$ and K_i are the output i_{th} unit in micro-grid and its operation and maintenance ratio, N_e is the total number of units, μ_j is cost paid per gram for the j_{th} pollution, ω_{ij} is the j_{th} emission's gram per kW by the i_{th} unit, and N_e is the type of pollution, including carbides, sulfides and nitrides. Because PV and WT are renewable energy, their environmental impacts are ignored.

4.3 Constraint Conditions

Power balance exists in every time steps *t*, namely:

$$P_{pv}(t) + P_{wt}(t) + P_{MT}(t) + P_t(t) + P_B(t) = l(t) \quad (11)$$

where $P_{pv}(t)$ and $P_{wt}(t)$ are output power of PV and WT.

As for the i_{th} unit, upper and lower limits of output power $P_i(t)$ are assumed:

$$P_{i,\min} \le P_i(t) \le P_{i,\max} \quad (12)$$

The constraint conditions *SOC* and N_B need to meet the follow equation:

$$\begin{cases} SOC_{\min} \le SOC(t) \le SOC_{\max} \\ N_B \le N_{B,\max} \end{cases} \quad (13)$$

BESS's initial status after a cycle should be balanced:

$$SOC(1) = SOC(T) \quad (14)$$

4.4 Solution Method

The mainly variables in the second-stage model are $P_B(t)$, $P_{MT}(t)$, and $P_t(t)$. These variables turn the problem into a nonlinear problem with multiple constraints.

Since BESS can hardly charge and discharge at the same time, its output can be expressed as:

$$P_B(t) = B_{dis}(t)P_{dis}(t) - B_{ch}(t)P_{ch}(t) \quad (15)$$

where $B_{dis}(t)$ and $B_{ch}(t)$ are binary numbers. BESS can only be charged or discharged at certain time, so the follow equation is met.

$$0 \le B_{dis}(t) + B_{ch}(t) \le 1 \quad (16)$$

Meanwhile, to solve the second stage more easily, the nonlinear problem needs to be transferred to a linear issue. Therefore, we apply the method in [18] to get its subsection linearization output. Lastly, the second-stage model turns out to be a MILP problem, which can be solved by mathematical models solvers (e.g. CPLEX).

5. Case Study

A grid-connected micro-grid in an area in the north of China is performed on a test case. Parameters such as wind speed, temperature can be seen in Table I. Referring to Chinese market, power price depends on valley period. Power price [18] and electrical load of users in micro-grid are shown in Fig.3 and Fig.4 respectively. Pollution emission coefficients in environment and other parameters are seen in Table II and III [19].

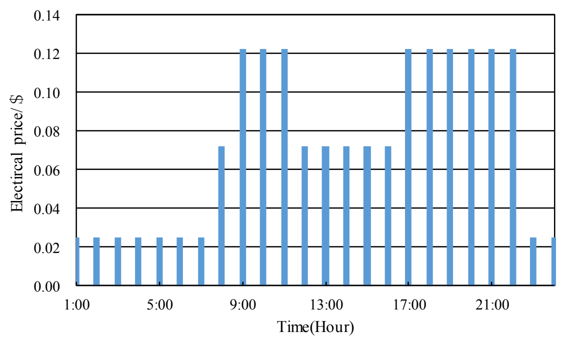

Figure 3. Price of TOU(Time Of Use)

TABLE I. PARAMETERS OF WIND POWER AND PHOTOVALTIC

t/h	v/(m/s)	G_T/(W/m^2)	T_τ/°C	t	v	G_T	T_τ
1	9.1	0	12.3	13	10.5	284.8	20.9
2	8.9	0	11.7	14	9.9	237.2	20.1
3	8.5	0	11.5	15	9.9	226.2	20.7
4	7.5	0	12.7	16	10.4	171.4	20.3
5	8.0	0	13.4	17	9.1	112.7	20.2
6	7.8	0	13.2	18	9.1	8.3	18.5
7	8.6	13.8	14.2	19	9.8	0	16.3
8	8.7	36.8	14.4	20	10.4	0	16.2
9	9.9	85.9	16.8	21	11.1	0	15.2
10	9.3	129.9	17.3	22	9.8	0	14.5
11	11.2	182.5	17.8	23	10.0	0	14.5
12	11.4	247.0	18.8	24	10.1	0	14.2

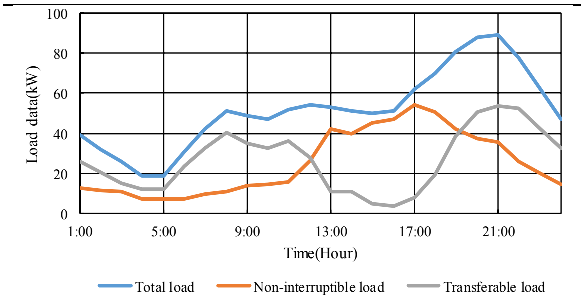

Figure 4. The Curves of different load

Day-ahead dispatch of micro-grid is performed is this paper, and dispatch time interval is one hour, which is to say $N = 24$ and $\Delta t = 1h$. The capacity of BESS is 100kWh, and the range of SOC is 0.2 to 1.0. $\eta_{ch} = \eta_{dis} = 0.9$, and rated charging and discharging power are both 20kW. v_{ci}=2.5. v_{co}=10, v_r=11, A=-0.0062, B=0.1914, C=-0.4473, D=0.1066. The output of WT and PV in a day are shown in Fig.5. It can been seen that the results of WT and PV are tightly close to their maximum output, which fit the economic operation rules of micro-grid, whose reason is that cleanable energy such as wind and photovoltaic produces few pollutants, no environment cost is included.

TABLE II. POLLUTANT EMISSION PARAMETERS

Pollution	Carbide	Sulfide	Nitrides
MT(g/kWh)	725	2.28	1.82
Distributed Network(g/kWh)	889	3.15	2.35

TABLE III. PARAMETERS OF DISTRIBUTED GENERATIONS

Unit	Upper bound(kW)	Lower bound(kW)	Operation/Maintenance Cost（￥/kWh）
WT	0	12	0.0296
PV	0	6	0.0832
MT	15	65	0.0250

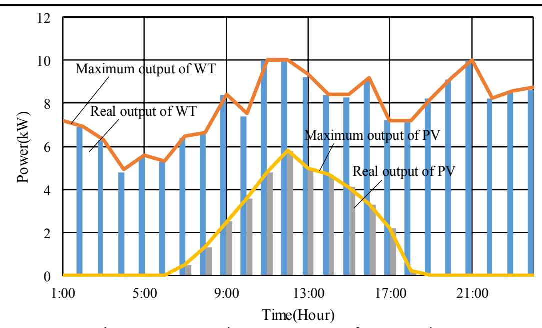

Figure 5. Maximum output of WT and PV

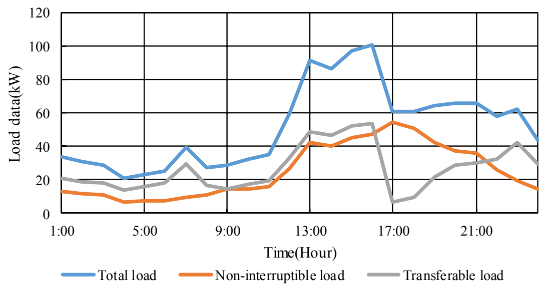

Figure 6. The Curves of different loads after optimization

Fig.6 shows the results of load curve after the first-stage optimization. It can be seen that parts of load used in high price period are transferred to low price period. That is to say, peak shaving and valley filling is achieved in the certain extent. However, due to restrictions of user satisfaction, not all the transferable load goes to the low price period totally, especially after 23:00. The result conforms to users' behaviors, which also illustrates the rationality of the proposed first stage model.

Fig.7 illustrates the operation curves of micro-grid after optimization on the basis of first stage method. It can be seen that shortage of power is filled by MT, distributed network and BESS, since PV and WT cannot supply all the power. BESS charge after 23:00, and discharge in high price period, the economic operation of micro-grid is illustrated.

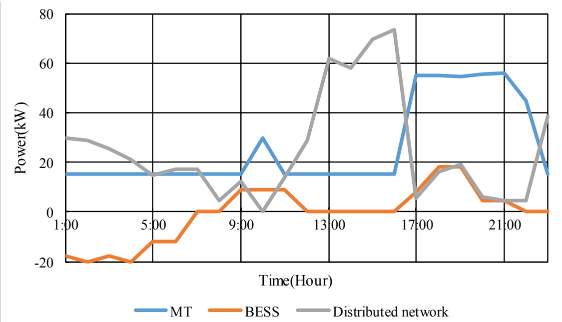

Figure 7. Optimal dispatching curves considering load characteristic

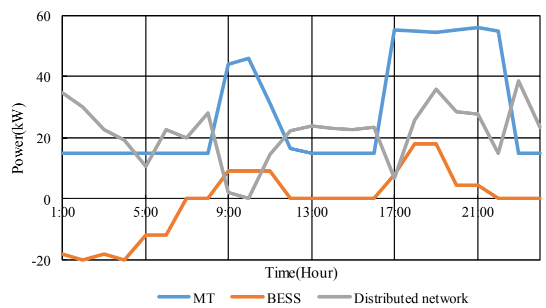

Figure 8. Optimal dispatching curves without considering load characteristic

From Fig.8, it can be easily seen that the trends of MT's output and power exchanged with distributed network are roughly identical. Because the method that solve micro-grid operation problem is the same. The difference is the load curve. But the two-stage micro-grid operation optimization considers more comprehensive factors. Fig.9 shows the costs of two situations, from which it can be concluded that costs are reduced by 4.23%.

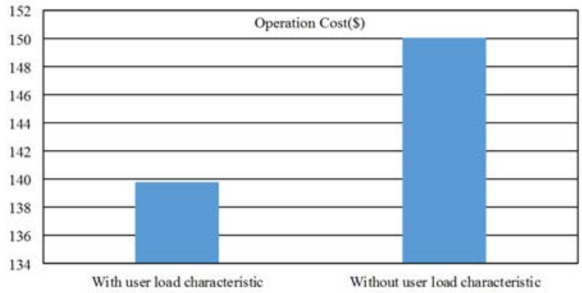

Figure 9. Comparison of operation cost under two modes

6. Conclusion

In this paper, a two-stage optimization method based on user characteristics is applied to a micro-grid for the sake of improving the economic operational micro-grid. The first stage mainly consider the user's satisfaction to adjust load, PSO algorithm is introduced to solve the nonlinear issue. While the second stage is aimed at reducing operational cost on the basis of the first stage. The second stage model is turned into a MILP problem solved by CPLEX. The results of a test case show that operational costs are reduced based on the proposed model in this paper.

References

[1] J. A. P. Lopes, C .L . Moreira, and A.G. Madureira, "Defining control strategies for micro-grids islanded operation," IEEE Trans. Power Systems, vol. 21, pp. 916-924, May. 2006.

[2] S. Conti, R. Nicolosi, S. A. Rizzo, and H. H. Zeineldin, "Optimal dispatching of distributed generators and storage systems for MV islanded micro-grids," IEEE Trans. Power Delivery, vol. 27, pp. 1243 – 1251, May. 2012.

[3] L. Guo , W. Liu , J. Cai , B. Hong and C. Wang, "A two-stage optimal planning and design method for combined cooling , heat and power micro-grid system," Energy Conversion and Management, vol. 74, pp. 433-445, Oct. 2013.

[4] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, "Smart energy management system for optimal micro-grid economic operation," IET Renewable Power Generation, vol. 5, pp. 258-267, Apr. 2011.

[5] J. Li, Y. Liu, and L. Wu, "Optimal operation for community based multi-party micro-grid in grid-connected and islanded modes," IEEE Tran. Smart Grid, vol. pp, pp. 1-1, May. 2017.

[6] T. A. Nguyen and M. L. Crow, "Stochastic optimization of renewable-based micro-grid operation incorporating battery operating cost," IEEE Tran. Power Systems, vol. 31, pp. 2289–2296, Jul. 2017.

[7] J. Joo and M. D. Ilić, "An information exchange framework utilizing smart buildings for efficient micro-grid operation," Proceedings of the IEEE, vol. 104, pp. 858–864, Mar. 2016.

[8] Z. Ding and W. Lee, "A stochastic micro-grid operation scheme to balance between system reliability and greenhouse gas emission," IEEE Trans. Industry Applications, vol. 52, pp. 1157–1166, Oct. 2015.

[9] H. Wang and J. Huang, "Joint investment and operation of micro-grid," IEEE Trans. Smart Grid, vol. 8, pp. 883-845, Dec. 2017.
[10] E. Craparoa, M. Karatasb and D. I. Singhama, "A robust optimization approach to hybrid micro-grid operation using ensemble weather forecasts," Applied Energy, vol. 201, pp. 135-147, Sep. 2017.
[11] J. Ma, H. H. Chen and L. Song, "Residential load scheduling in smart grid: a cost efficiency perspective," IEEE Trans. Smart Grid, vol. 7, pp. 771-784, Mar. 2016.
[12] P. Samadi, V. W. S. Wong and Robert Schober, "Load scheduling and power trading in systems with high penetration of renewable energy resources," IEEE Trans. Smart Grid, vol. 7, pp. 1802-1812, Jun. 2016.
[13] L. K. Panwar, S. R. Konda, A. Verma, B. K. Panigrahi and R. Kumar, "Demand response aggregator coordinated two-stage responsive load scheduling in distribution system considering customer behaviour," IET Generation, Transmission & Distribution, vol. 11, pp. 1023-1032, Mar. 2017.
[14] T. Li and M. Dong, "Real-time residential-side joint energy storage management and load scheduling with renewable integration," IEEE Trans. Smart Grid, vol. 99, pp. 1-15, Apr. 2017.
[15] C. Wang, Y. Zhou, J. Wu, J. Wang, Y. Zhang and D. Wang, "Robust-index method for household load scheduling considering uncertainties of customer behavior," IEEE Trans. Smart Grid, vol. 6, pp. 1806-1818, Mar. 2015.
[16] A. Agnetis, G. Pascale, P. Detti and Antonio Vicino, "Load scheduling for household energy consumption optimization," IEEE Trans. Smart Grid, vol. 4, pp. 2364-2373, Apr. 2013.
[17] C. Li, Y. Chen, J. Zeng, and J. Liu, "Research on optimization algorithm of micro-grid energy management system based on non-cooperative game theory," Power System Technology, vol. 40, pp. 387-395, Feb, 2016.
[18] X. Wu, X. Wang, J. Wang, and Z. Bie, "Economic generation scheduling of a micro-grid using mixed integer programming," Proceedings of the CSEE, vol. 33, pp. 1-8, Oct. 2013.
[19] X. Chen, Z. Yang, C. Jing, M. Liao, S. Lin and Q. Wu, "Economic optimization for the combined cooling, heating and power system with micro-turbine," Southern Power System Technology, vol. 2, pp. 1-8, Jun. 2014.