Adjustable Residential Loads Management under Electricity Prosumers Network

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Abstract:

One important concept in the future power system is electricity prosumer, which can be both electricity producer and consumer at different times. Due to prosumer's abilities, each prosumer can buy electricity from neighboring prosumers as well as the main grid. To properly manage the network of prosumers, an optimization problem is solved under the linear function submission-based double auction (LFS-DA) model. This work analyzes the effects of LFS-DA algorithm on adjustable loads in a network of prosumers. Each prosumer aims to minimize its cost which consists of the prosumer's dissatisfaction and the actual cost of buying electricity. Through simulations, it is shown that the electricity consumption for adjustable loads is controlled to minimize cost.

Keywords:

LFS-DA Algorithm, network of prosumers, demand side management

1. Introduction

1.1 The evolution of power grid

Unlike the traditional power grid, the modernized power grid considers sources of energy located near the end-users i.e. Distributed Energy resources (DERs) to produce energy. As far as loss reduction and environmental issues are concerned, emerging DERs such as Renewable Energy Sources (RESs) like solar photovoltaic (PV) and wind turbines are gaining momentum in the production of electric energy.

Another crucial concept in the modernized power grid is a "**prosumer**." With a prosumer, the bidirectional power flow is made possible. A prosumer is capable of consuming, producing and selling energy for different time slots. Figure 1 describes the abilities of a prosumer. Sha and Aiello [1] studied an energy exchange for prosumers, whereby the prosumer's energy is transmitted and exchanged as a commodity between end-users and the motivation for this trade is energy price.

In this study, a set of prosumers is considered. Each prosumer owns a solar PV panel, a battery storage unit and two types of loads i.e. basic residential loads [2] and adjustable loads. An optimization scheme is used to compute the energy consumption for adjustable loads. We consider Heating, Ventilation, Air Conditioning (HVAC) loads as typical and simulation example for adjustable loads.

Figure 1 Prosumer's abilities

Razzaq et al. [3] studied a prosumer-based energy management in order to achieve the demand side management while optimizing the cost for both prosumers and utilities. In [4], an energy management which helps prosumers to control their consumption in respect to controllable and uncontrollable generation was studied. Liu et al. [5] used a game theoretical approach to evaluate the benefits of PV solar owned prosumers. However, none of these previous works considered the matching of supply and demand in a network of prosumers. Matching the supply and demand is the work developed by Tadahiro et al. [6-7] under LFS-DA algorithm.

The contribution of this research is to study for each participating prosumer, the effects of LFS-DA algorithm on HVAC loads' energy consumption. The following key indicators are used to investigate the performance of the optimization scheme: (i) prosumer's energy cost and (ii) prosumers' dissatisfaction. Results show that each prosumer maximizes its HVAC energy consumption and therefore minimizes its dissatisfaction rate. Thus meeting the end-users' HVAC energy constraints. Reduction in Prosumers' dissatisfaction minimizes also the cost, and this is the goal of the objective function. Comparisons between the LFS-DA and individual algorithms have proven the outstanding performance of LFS-DA as a proper economic model to control adjustable residential loads.

The remainder of this paper is organized as follows. Section 2 discusses the optimization scheme and its modeling. Section 3 presents the simulation framework and presents the results. Section 4 concludes the paper.

2. Modeling of the optimization scheme

2.1 Optimization problem under LFS-DA

The paradigm shift in energy production has empowered prosumers to take part in energy transactions. Communications between prosumers are facilitated by an auctioneer (i.e. regional market platform). Previous researches have used time-of-use (TOU) pricing, real-time pricing (RTP) methods in order to control the electricity demand for consumers [6]. Tadahiro and Al. [6-7] studied the relationship between LFS-DA and RTP, used the LFS-DA to control a network of prosumers in order to maximize their welfare.

We consider the state vector described in section 2.2 for each prosumer and we briefly present the LFS-DA in Algorithm 1.

Algorithm 1. LFS-DA

1: $k \leftarrow 0$
2: Initialization of the price $p^{(k)} = \left(p_t^{(k)}\right) t \in T$
3: **repeat**
//each agent solves equation (5) using constraints (6)-(16)
4: Update the state vector X_i with respect to $p^{(k)}$
5: Update $\alpha_i^{*t} \leftarrow \beta_i^t p_t^{(k)} + (m_i^b - m_i^s)$
//each agent submits $(\alpha_i^{*t}, \beta_i^t)$ to the auctioneer
6: Update $p^{(k+1)} \leftarrow market\_clearing(\alpha_i^t, \beta_i^t)$ from all prosumers and to all time slots
7: Update the bidding parameters
//reconfiguration by each prosumer
8: Reconfigure the state vector in order to meet constraint (15)
9: $k \leftarrow k + 1$
10: **until** a stopping criterion is reached
11: **return** the state vector X_i and the regional price

The bidding parameters in LFS-DA are linear functions. Hence the supply and the demand are given by the following equations:

$$m_i^s = \max(\beta_i^t p_t - \alpha_i^t, 0) \quad (1)$$

$$m_i^b = \max(-\beta_i^t p_t + \alpha_i^t, 0), \quad (2)$$

where β_i^t is a fixed positive constant, and α_i^t is a variable depending on β_i^t and the fluctuation between the supply and the demand for each prosumer. The market clearing price p_t is calculated at supply-demand equilibrium and is given by:

$$p_t = \frac{(\gamma \alpha_i^t)_{sellers} + (\alpha_i^t)_{buyers}}{(\gamma \beta_i^t)_{sellers} + (\beta_i^t)_{buyers}}. \quad (3)$$

For a seller, $\frac{\alpha_i^t}{\beta_i^t} \leq p_t$ and for a buyer, $\frac{\alpha_i^t}{\beta_i^t} > p_t$

More detailed description for the LFS-DA algorithm, we refer to [6].

2.2 Objective function formulation

Various demand side techniques have been used in order to control the electricity demand for end-users. In this research, controlling the adjustable residential loads while meeting home appliances constraints is a concurrent task with controlling the supply because it is modeled under the LFS-DA scheme. Figure 2 shows an example of a prosumer network. Each prosumer (i.e. residential home) is represented by its smart meter. The smart meter will trade on behalf of the homeowner. The state vector of i-th prosumer is a set composed of nine variables each varying with time slots t.

$$X_i \triangleq \{l_i^b, h_i^t, l_i^g, b_i^c, b_i^d, m_i^b, m_i^s, g_i^b, g_i^s\},$$

where l_i^b, h_i^t, l_i^g, b_i^c, b_i^d, m_i^b, m_i^s, g_i^b and g_i^s denote basic residential load, HVAC load, solar PV generation, battery charging, battery discharging, energy bought from prosumers' network, energy sold to prosumers' network, energy bought from main grid and energy sold to main grid respectively.

Battery charging or discharging, trading with the main grid or regional market depends on the surplus (production exceeds consumption) or deficit (consumption exceeds production) in electric energy for each prosumer. In this formulation, we also consider the battery charging efficiency and the transmission line efficiency. Another motivating factor is that prosumers prefer trading between themselves before trading with the main grid (i.e. utility).

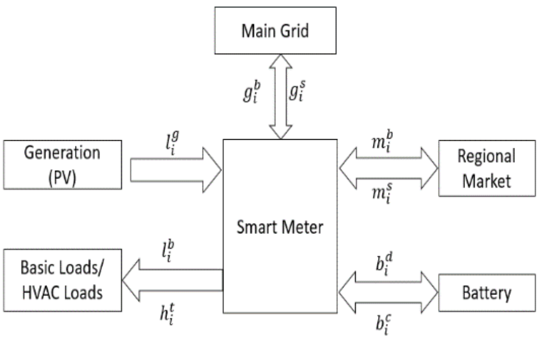

Figure 2 Prosumer's topology

Prosumers participating in trading auctions will submit or ask bids to/from the regional market, an auctioneer, a platform interconnecting all present prosumers.

Now, we formulate the optimization problem. Given that we want to minimize prosumers' energy cost and dissatisfaction, our problem is a minimization problem. We fix our attention on minimizing the operational cost and the prosumer's dissatisfaction. The cost for i-th prosumer is defined as follows (there are N prosumers in total).

$$C_i(X_i,\boldsymbol{p}) = \sum_{t\in T} y_i^t(h_i^t) + C_i^t(l_i^g) - \gamma p_t^s g_i^s + p_t^b g_i^b - \gamma p_t m_i^s + p_t m_i^b \qquad (4)$$

The left member of equation (4) expresses the operational cost which is a function of the state vector defined above and a price $\boldsymbol{p} \triangleq \{p_t^s, p_t^b, p_t\}$, which represents the price for selling/buying to/from main grid and the regional market price. $y_i^t(h_i^t)$, $C_i^t(l_i^g)$ and γ represent the prosumer's dissatisfaction, the cost of electricity generation and the transmission line efficiency respectively. As it is expressed by constraint (16), we chose the dissatisfaction function to be a quadratic function of which the domain of HVAC consumption is $[h_i^{min}, h_i^{max}]$ and h_i^{diss} being a desirable set point where a minimum dissatisfaction is achievable [8].

Therefore, the above formulation allows us to write the minimization problem as follows:

$$\min \sum_{i\in N} C_i(X_i,\boldsymbol{p}) \qquad (5)$$

Subject to the following constraints:

$$g_i^s \geq 0 \qquad (6)$$

$$l_i^b \geq l_i^{b,min} \qquad (7)$$

$$0 \leq l_i^g \leq l_i^{g,max} \qquad (8)$$

$$0 \leq m_i^s \leq m_i^{s,max} \qquad (9)$$

$$0 \leq m_i^b \leq m_i^{b,max} \qquad (10)$$

$$0 \leq b_i^c \leq b_i^{c,max} \qquad (11)$$

$$0 \leq b_i^d \leq b_i^{d,max} \qquad (12)$$

$$0 \leq g_i^b \leq g_i^{b,max} \qquad (13)$$

$$0 \leq s_i^{init} + \textstyle\sum_i^t (\eta_i b_i^c - b_i^d) \leq s_i^{max} \qquad (14)$$

$$h_i^t + l_i^b - l_i^g + b_i^c - b_i^d + m_i^s - m_i^b + g_i^s - g_i^b = 0 \qquad (15)$$

$$y_i^t(h_i^t) = \begin{cases} w_i^t\left(h_i^{diss} - h_i^t\right)^2, & if\ h_i^{min} \leq h_i^t \leq h_i^{max} \\ 0\,, & otherwise \end{cases} \qquad (16)$$

The description of parameters is in Table 1.

3. Simulation, Results, and Discussion

3.1 Simulation environment

We simulate the performance of LFS-DA in terms of electricity cost and dissatisfaction. The results are compared with individual case which has no electricity exchange between customers, i.e., traditional case. For simplicity, we consider two prosumers (note that this model is applicable to more than two prosumers) owning solar PV cells as their DER. The generation and basic residential load profiles of the two prosumers are given by Fig. 3.

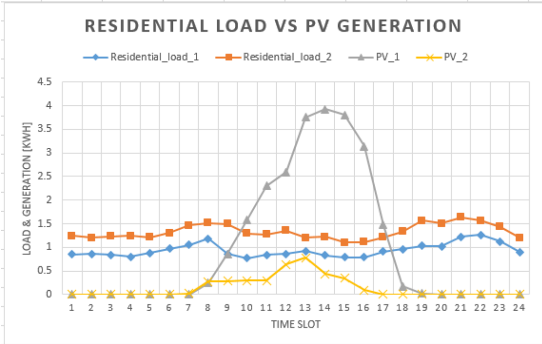

Figure 3 Prosumers' generation and basic loads

Data for solar PV generations have taken from the US residential values measured on March 19, 2017 (For McPherson Residence, 4.250kW and FVE Velve Paka 139, 1.896kW) [9]. Looking at the situation provided by Fig. 3, one could notice that prosumer 1 has some surplus for day time slots yet prosumer 2 has a deficit of energy. All other parameters used for simulation are described in Table 1.

Table 1 Parameters used for simulation

Parameters and variables of simulation	
Number of prosumers	N=2 households
Time slots	T=24hrs with 1h for each time slot
Battery bounds	$b_i^{c,max} = b_i^{d,max} = 4$ [kWh]
Regional market bounds	$m_i^{s,max} = m_i^{b,max} = 20$ [kWh]
Battery state of charge	$s_i^{init} = 0, s_i^{max} = 20$ [kWh]
Maximum buying from main grid	$g_i^{b,max} = 500$ [kWh]
Battery efficiency	$\eta_i = 0.85$
Transmission efficiency	$\gamma = 0.95$
PV generation cost	$C_i^t = 0$
HVAC load bounds	$h_i^{min} = 0, h_i^{max} =$ 4 [kWh]
Dissatisfaction weight parameter	$w_i^t = 200$
Constant h_i^{diss}	1-9[AM]; $h_i^{diss} = 0$ 10AM-20PM; $h_i^{diss} = 1.2$ 21-24[PM]; $h_i^{diss} = 0$

HVAC loads are constrained to consume energy from 10 am to 8 pm, a schedule for 11hours. We use the Korean Electric Power Corporation price profile for the main grid [10].

Table 2 Prosumers' total cost dissection

	$\sum_{t\in T} y_i^t(h_i^t)$		$\sum_{t\in T} p_t^b g_i^b$		$\sum_{t\in T} \gamma p_t m_i^s$		$\sum_{t\in T} p_t m_i^b$		$C_i(X_i,p)$	
	P1	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**	**P1**	**P2**
LFS-DA	49.94	52.82	1,082.21	1,971.12	471.21	0	0	471.21	660.95	2,495.15
Individual	48.50	159.49	647.75	2,627.39	-	-	-	-	696.26	2,786.88

3.2 Results and Discussion

The outcomes of this work are discussed in two scenarios. In scenario 1 there is regional trading between prosumers and in scenario 2 there is no trading and each prosumer acts individually to suffice its load requirements.

a. Scenario 1 (LFS-DA)

In this scenario, scheduling results show that prosumers buy energy from main grid to meet their load requirements during the time when the PV generation is nonexistent. Prosumers also trade between themselves when the price of regional market is less than that of the main grid. Battery scheduling also contributes to supply energy when necessary. Figure 4 shows that HVAC loads consume energy to minimize dissatisfaction. The dissatisfaction is between 3.75 and 5.20

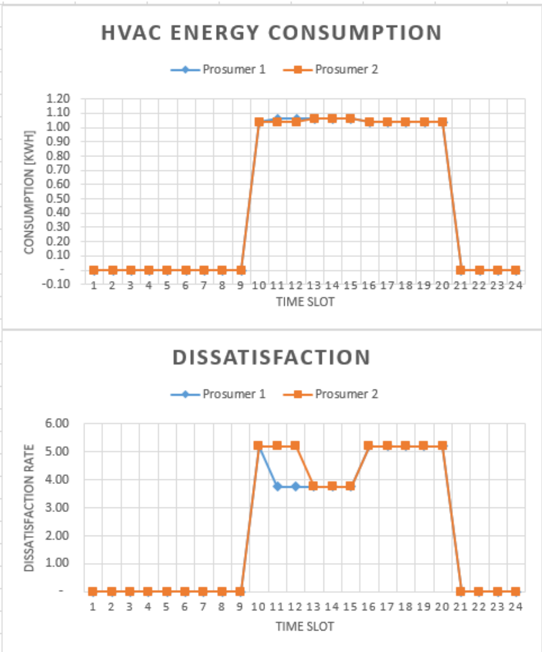

Figure 4 HVAC schedule & Dissatisfaction

b. Scenario 2

In this scenario, each prosumer individually uses its own generation and battery to supply its load. When its generation is insufficient to supply all loads, the prosumer buys electricity from the main grid. Figure 5 represents the HVAC scheduling and the resulting dissatisfaction rate. The dissatisfaction is between 3.75 and 14.50.

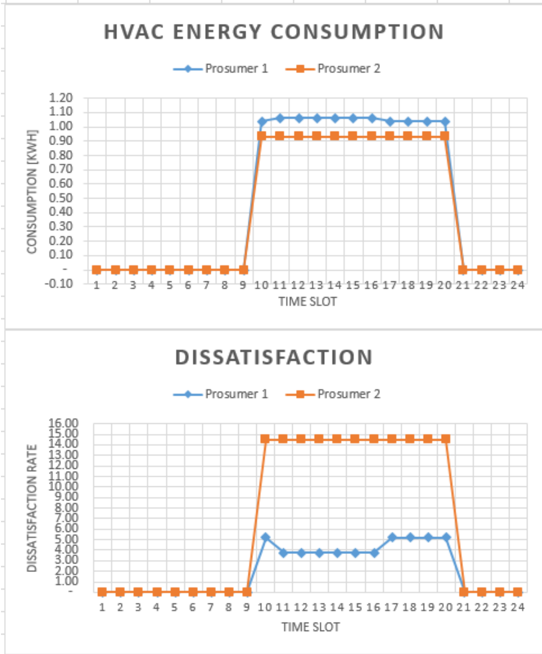

Figure 5 HVAC schedule & Dissatisfaction

To properly understand the influence that the dissatisfaction has on prosumer's energy consumption cost, we calculate the total cost for energy consumption. We also show the contribution of each term of the objective function by providing its total cost in a schedule of 24hrs. The values are given in the Table 2. P1 and P2 stand for prosumer 1 and prosumer 2. Table 2 shows that a prosumer with deficit in energy can only minimize its dissatisfaction by participating in regional market. This explains the difference in dissatisfaction rate for prosumer 2. A total cost of **3,156.09** vs a total cost of **3,483.14** for all prosumers has been observed in favor of LFS-DA.

We also compare the price profiles of the main grid and that of the regional market during the trading timing. Figure 6 shows the result. It is seen that during day time when PV generation is available, the regional market price is less than that of the main grid. Therefore, prosumers can trade between themselves. During night, they buy energy from the main grid.

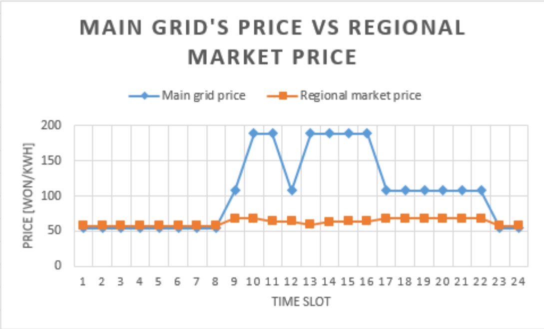

Figure 6 Price profiles

4. Conclusion

Nowadays producing electricity is not seen only as a task for utilities but prosumers are also involved in the production. The introduction of renewable energy sources in the power system is revolutionizing the power grid and thus affects our life, health, and environment. In this work, we considered a network of prosumers each owning a solar PV. An optimization problem is modeled and solved under the LFS-DA model in order to manage HVAC loads. We focused on HVAC energy consumption's control as a key element to reducing the cost. Simulation results have proven that trading with other prosumers in their network is more beneficial than being alone (9.4% reduction of total cost) and want to suffice its load requirements.

In future works, we will extend this model to building loads and electric vehicles. We think to further introducing the comfort zone as a new constraint variable to control the HVAC.

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References

[1] A. Sha and M. Aiello, "A Novel Strategy for Optimising Decentralized Energy Exchange for Prosumers", *MDPI, Energies* 2016, 9, 554; doi:10.3390/en9070554

[2] "Hourly Load Profiles", Internet: https://www.xcelenergy.com/staticfiles/xe/Corporate/Corporate%20PDFs/AppendixD-Hourly_Load_Profiles.pdf [Mar. 06, 2017]

[3] S.Razzaq, R.Zafar, N.A.Khan, A.R. Butt, and A. Mahmood "A Novel Prosumer-Based Energy Sharing and Management (PESM) Approach for Cooperative Demand Side Management (DSM) in Smart Grid", *MDPI*, *Appl. Sci.* 2016, 6, 275; doi:10.3390/app6100275

[4] R.Verschae, T.Kato, and T.Matsuyama, "Energy Management in Prosumer Communities: A Coordinated Approach", *MDPI, Energies* 2016, 9, 562; doi:10.3390/en9070562

[5] N. Liu, C.Wang, X.Lin, and J.Lei, "Multi-Party Energy Management for Clusters of Roof Leased PV Prosumers: A Game Theoretical Approach", *MDPI, Energies* 2016, 9, 536; doi:10.3390/en9070536

[6] T. Tadahiro, K. Kawasaki, Y. Fukui, T.Takata, and S. Yano, "Automated Linear Function Submission-Based Double Auction as Bottom-up Real-Time Pricing in a Regional Prosumers' Electricity Network", *MDPI*, *Energies* 2015,8,7381-7406; doi:10.3390/en8077381

[7] T. Tadahiro, T. Takata, Y. Fukui and K. Kawasaki, "Convergent Double Auction Mechanism for a Prosumers' Decentralized Smart Grid", *MDPI, Energies* 2015, 8, 12342-12361; doi: 10.3390/en81112315

[8] N. Gatsis and G.B. Giannakis, "Residential Load Control: Distributed Scheduling and Convergence with Lost AMI Messages", *IEEE Trans. on Smart Grid*, Vol.3.No.2, Jun. 2012

[9] "PV Output", Internet: https://pvoutput.org/outputs.jsp [Mar. 19, 2017]

[10] "Electric rates Table," Internet: http://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00203.jsp [Mar. 06, 2017]

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