Operations of Energy Management System in a Smart Grid and Consumer Behavior

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Abstract :

In a smart grid, it becomes easier for electricity consumers to automatically control energy consumption by energy management system along with consumption preference. This paper proposes an operations model reflecting consumers' dynamically changing preference that they want to change energy consumption over dynamically changing electricity prices. Also, we investigate the impact of consumers' behavior or characteristics on the energy consumption. Based on the proposed model, we found that consumers reduce or increase energy consumption when prices go up or down, respectively. Obviously, this result could be expected by the demand response in a smart grid to reduce peak time demand by controlling prices. However, more important thing is that sometimes too high consumers' sensitivity could incur another peak consumption during off-peak time period, if energy prices are not determined in real time but given exogenously or in advance.

Keywords-component; *Energy Management System; Consumer Behavior; Price Elasticity; Smart Grid*

I. Introduction and literature review

In a smart grid, an electricity market controls electricity prices continuously to balance supply and demand. Therefore, if we have high demand for the electricity during a certain time period, the price will be determined at a high level, and vice versa. Besides, the demand for electricity is very fluctuant over time and uncertain, which implies the prices of electricity is also quite fluctuant. Also, consumers can easily recognize the price changes through advanced metering infrastructure (AMI) and home area network (HAN) accompanying with energy management system (EMS) ([1]). Therefore, consumers can control energy consumption depending on the energy prices. For this reason, many firms regarding energy and information systems have developed energy management systems which could automatically control energy consumption. However, those energy management system only can provide recommendations or guidelines which ask a consumer to make a decision between alternatives but cannot provide fully automatic control depending on consumer's consumption preference. Also, willingness to consume energy could change if the energy prices changes. Because prices changes over time, suggesting a guideline and making a decision over and over is not possible. Therefore, we need to develop a model which can optimize automatically energy consumption depending on consumer's preference or characteristics.

However, there are only few researches considering consumer's utility and behavior. [2-4] have discussed and proposed real time pricing models, but the most challenging thing is that they assumed maximum energy consumption does not change or does not consider consumer's behavior such as reduction of consumption in case of rising prices. To expand a smart grid and demand response, [5] emphasized the importance of consideration of households and commercial customers. Furthermore, when the consumer's behavior is taken into account, it is quite meaningful to know what change could be made.

Therefore, this research is willing to provide an operations model for energy management system considering consumer's behavior and to discuss how decision-making regarding energy consumption might change. In this paper, we focused specifically on the relationship between consumer characteristics like price-sensitivity and energy consumption. The structure of this paper is as follows. In Section 2, we simply introduce a new model to optimally determine energy consumption. Then, in Section 3, from the proposed model, simulation and analysis will be executed to examine how the decision could be changed due to consumer's characteristics. Section 5 summarizes major results, and provides managerial implications and future research.

II. Mathematical Model

In this section, we develop a mathematical operations model for energy management system incorporating consumer's utility which can provide a set of optimized energy consumption solutions. The variables and parameters to develop our model are given as follows:

$\lambda(t)$ = electricity price at time *t*

$e(t)$ = energy consumption at time *t*

e_{sum}^{min} = minimum energy consumption during time [0,*T*]

$e^{min}(t)$ = minimum energy consumption at time *t*

$e^{max}(t)$ = maximum allowance of energy consumption at time *t* with considering consumer behavior

$\gamma(t)$ = maximum energy consumption without considering consumer behavior

$\delta(t)$ = price elasticity over electricity price

$u(e(t))$ = utility function according to energy consumption

Along with given variables, our proposed model is given as follows:

$$\min \quad \sum_{t=1}^{T} \lambda(t)e(t) - u\big(e(t)\big) \tag{1}$$

$$\text{s.t.} \quad \sum_{t=1}^{T} e(t) \geq e_{sum}^{min} \tag{2}$$

$$e(t) \geq e^{min}(t), \quad \forall t \in \{1, T\} \tag{3}$$

$$e(t) \leq e^{max}(t) = \gamma(t) - \delta(t)\big(\lambda(t) - \lambda(t-1)\big) \quad for\ t = 2,3, \dots, T \tag{4}$$

$$u\big(e(t)\big) = u_1 \log(u_2 e(t) + u_3) \tag{5}$$

$$e(t) \geq 0, \quad \forall t \in \{1, T\} \tag{6}$$

$$\lambda(t) \geq 0, \quad \forall t \in \{1, T\} \tag{7}$$

$$where \quad \delta(t) \geq 0\ and\ \gamma(t) \geq 0.$$

For the above model, the objective of a consumer is to minimize payments of energy and maximize the satisfaction from energy consumption, which are expressed as “(1)”. Also, total energy consumption has a lower limit because appliances or equipment require energy at more than a certain level, so we addressed “(2)”. Besides, at a given time *t*, we have minimum and maximum consumption as described in “(3)” and “(4)”. However, in “(4)”, we added consumer’s behavior as described in Figure 1 unlike traditional models like [6, 7]. This implies that a consumer can change the maximum allowance of energy consumption after checking energy prices. For example, if energy price goes up, the consumer will be afraid of paying more money than before. In this case, the consumer will try to reduce energy consumption. On the other hand, the consumer will be relaxed to use more energy and so the maximum allowance of energy consumption will increase. Then, the consumer might want to optimize consumption by compare payment and utility.

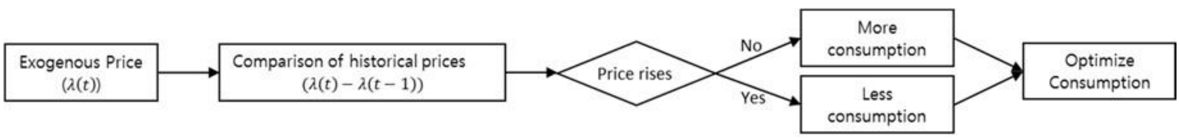

Figure 1. Logic of consumer behavior in the mathematical model

In addition, “(5)” explains the utility function in “(1)” which explains phenomenon that consumer’s satisfaction increases as consumption increases but the increment of satisfaction decreases. Besides, we have non-negativity conditions for variables and parameters in “(6)” and “(7)”.

III. Simulation and Analysis

This section examines the impacts of consumers’ behavior on energy consumption. Data for this analysis of a base scenario basis on the following table. Herein, the variable , a part of maximum allowance of energy consumption ( ), is expressed as / , which implies the assumption that, if consumer does not respond to price, maximum energy consumption might be times more than minimum energy consumption ( ). The simulations and analyses are run in MATLAB and GAMS with MINOS solver.

TABLE I. PARAMETERS AND VALUES FOR A BASE SCENARIO

Parameter	Value	Parameter	Value
$e^{min}(t)$	$\frac{e^{min}_{sum}}{T} - 0.5 * (t-12)^2$	e^{min}_{sum}	20000
$\Psi(t)$	$200 - 0.3 * (t-12)^2$	u_1	15000
δ	0	u_2, u_3	1
Maximum allowance(γ_1/e^{min})	1.2		

Based on the parameters, we first investigate the impact of price elasticity ( ) on energy consumption with four different scenarios. Each scenario is the case of =0, 15, 30, and 45, respectively. This represents the characteristic of consumer, which implies that the higher value of means more price-sensitive consumer. As described in Figure 2.a, volatility of energy consumption of Case 4 (=45) is very high compared to the others. Interestingly, the consumer responds to the energy prices only when the price is lower, but for the most cases during peak time consumers does not respond at all. This result could be expected by the demand response in a smart grid to reduce peak time demand by controlling prices. However, more important thing is that sometimes consumers' sensitivity could evoke another peak as shown during off-peak time period, if energy prices are not in real time but given exogenously or in advance.

Then, we examine the impact of utility ( ) on the consumption with three scenarios, which are the scenario 1 (15000), scenario 2 (150000) and scenario 3 (1500000). These scenarios mean that if consumer prefer consuming energy to paying electricity fee, the consumer will have larger . As described in Figure 2, we can notice that not responding area during peak-time period becomes smaller when the value becomes larger.

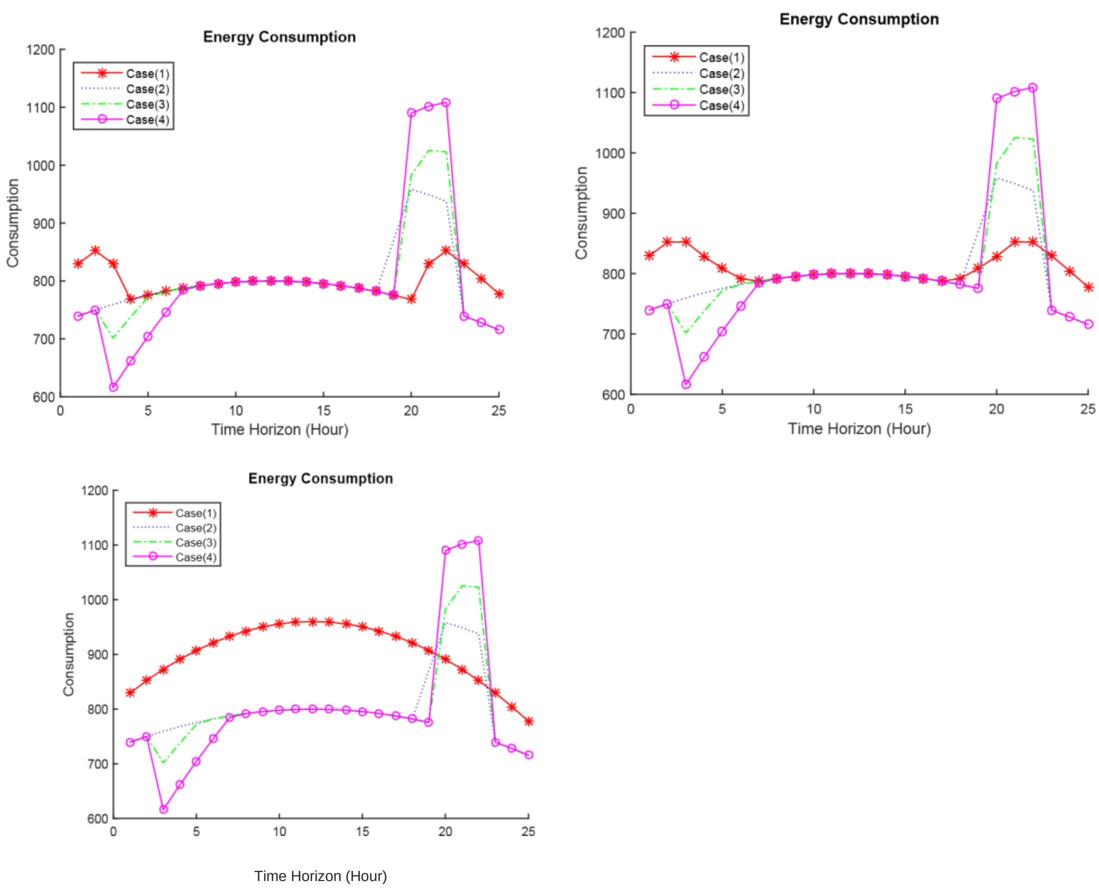

Figure 2. The impact of consumer's utility on energy consumption (a. Scenario 1 at left-top (15000), b. Scenario 2 at right-top (150000) c. Scenario 3 at left-bottom (1500000))

In addition, we exploit the impact of price elasticity ( ) on energy consumption with two sets of four different scenarios. Let us refer these two sets as Set1 and Set 2. Set 1 is the set of =0, 15, 30, and 45, while Set 2 is the set of =0, 6, 12, and 18, respectively. Also we repeat this analysis for two different values of , which we call Set 3 and Set 4 similarly. When we compare Set 1 to Set 2, we can notice that there is difference over the early times. More specifically, our result shows a less price-sensitive consumer will maximize consumption even when energy prices rise. This similarly happens to Set 3 and 4. However, if we compare Set 1 and 2 to Set 3 and 4, in other words if utility of consumption increases, we can see that energy consumption over the early times incurs.

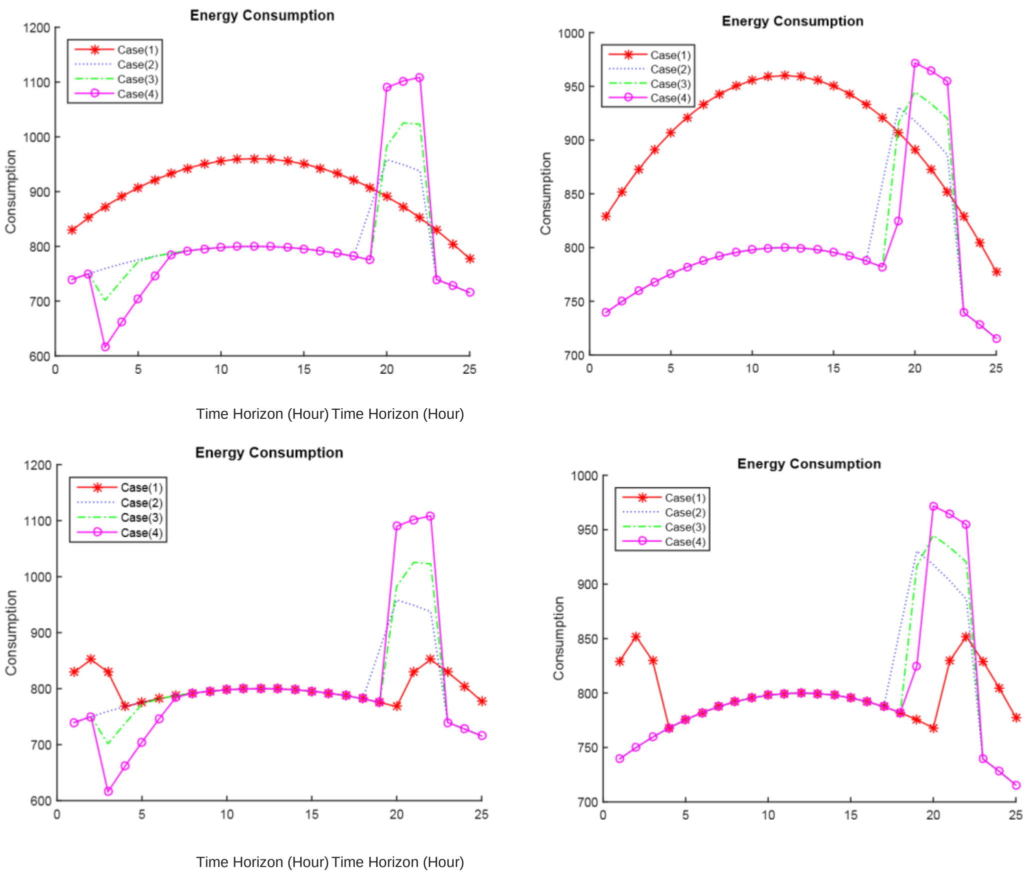

Figure 3. The impact of price elasticity on energy consumption (a. Set 1 at left-top (=0, 15, 30, and 45, 15000), b. Set 2 at right-top (=0, 6, 12, and 18, 15000) c. Set 3 at left-bottom (=0, 15, 30, and 45, 1500000) d. Set 4 at right-bottom (=0, 6, 12, and 18 1500000))

IV. Conclusion and future study

This paper proposes a model for operations reflecting consumers' preference that they want to change energy consumption over dynamically changing electricity prices. Also, we investigate the impact of consumers' behavior on the energy consumption. As mentioned in previous literature [5], to achieve more efficient and effective power grid, demand response system or energy management system especially for end users and commercial users needs to be prior. Of course, existing literature and models can help consumers' controlling energy consumption by providing guidelines to make decisions. However, because if energy management system can make decisions automatically, it would improve consumers' welfare more. For this reason, we provide a novel model considering consumers' consumption preference.

Based on our model, we have shown that a consumer reduces energy consumption when prices go up and sometimes increases consumption during off-peak time. Obviously, this result could be expected by the demand response in a smart grid to reduce peak time demand by controlling prices. However, more important thing is that sometimes high consumers' sensitivity could evoke another peak as shown during off-peak time period, if energy prices are not updated in real time but given exogenously or in advance.

As an extension of this research, the updating rule of prices can be considered. In this research, we assumed energy prices are given exogenously, just as nowadays implemented in one-day ahead market. However, in near future, the market prices will be noticed 15 minute ahead or in real time through AMI and HAN. Thus, energy consumption can affect the prices and the changed prices also change energy consumption again. Another extension of this research is to consider controlling home appliances automatically as discussed in [8]. More specifically, not all appliances or equipment can be smoothly controlled because properties of their works are different. Some appliance can be turned off but others may be not. For this reason, we can extend our model from more practical perspective.

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