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A Game Theory Approach for Maximum Utilization of Wind Power by DR in Residential Consumers

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***Abstract*—This paper proposes an indirect load control demand response (DR) strategy for residential houses. A Stackelberg game theory is applied to account for the interaction between the aggregator in one side and the consumers on the other side. The aggregator, which owns a wind power plant, strives to maximize wind power utilization by consumers. Therefore, it motivates the consumers to adjust their load demand according to the forecasted wind power production by offering a bonus to them. On the other hand, consumers attempt to achieve the highest amount of reward by changing their load profile. It is assumed that each consumer has a critical load of which they have no control, and also a flexible load such as heat, ventilation and air conditioning (HVAC) system which can regulate its demand while keeping the temperature in a specified band. In this way, the consumers' comfort level is entirely maintained. In addition, for the sake of considering the uncertainty, several scenarios for wind and also consumers' demand are considered in this work.**

***Index Terms*— Game theory, HVAC systems, indirect load control, stochastic programming.**

I. INTRODUCTION

Today, wind power generation constitutes a significant portion of power production around the world, with its share anticipated to grow even further in the near future. Wind power energy, as a prominent renewable energy source (RES), offers profitability and sustainability gains. In addition, it is accessible everywhere, especially with high potential at the offshore sites where establishing a wind power plant can also save lands. Besides these advantages, wind energy suffers from a major drawback as its power is highly fluctuating and unpredictable. Energy storage systems (ESSs) are known as an efficient way of coping with this problem, but they still impose high investment costs. Another issue is the degradation of ESSs, which implies its replacement by a new one at the end of its life expectancy. The other alternative for dealing with the fluctuating nature of wind power is activating demand response (DR) programs in end users [1].

Among DR approaches, the one that has attracted much attention is incentive-based DR. It works based on offering bonus to the consumers for motivating them to adjust their load profile for DR purpose. With the aim of considering a more effective method, a combination of the residential load model and also data acquired from a survey is used to predict the incentive-based DR at the level of each appliance [2]. In [3], a three level model was presented for demand side management with the consumers at the lower side ,which receive the bounus from aggregator and adjust their load, the DR aggregator in the middle position, which is given incentive by the utility, and the utility at the upper level, which strives for reducing the system operational cost.

Considering residential houses, thermostatically controlled loads (TCL) are an attractive option for DR programs, which have been recently used in a wide range. Heat, ventilation, and air conditioning (HVAC) systems are of TCLs type that have high power consumption and can be regarded as a great potential for this purpose. The physical features of various load have been taken into account to build a TCL model for appliances. Then, in [4], a methodology was suggested to involve the HVAC system, electric vehicle, and cloth dryer for the DR program. The TCL loads were used for improving the utilization of RESs in [5], [6]. In [5], a small load such as water heaters were used to be involved in the regulation services. In [6], with the intention of reducing the mismatch between wind power generation and consumers' demands, an optimal DR was proposed using a group of residential HVAC systems. However, the uncertainty associated with wind generation has not been considered in that paper. In [7], electric vehicle and battery energy storage were studied for providing extra flexibility in a stochastic way. In addition, various price-based DR programs have been considered for smarts houses to decide the best strategy for each of them. With the objective of investigating DR approach in a microgrid, a combination of RES, micro-CHP units, boiler, and an energy storage system were considered in [8] to supply the electrical and thermal load by adopting a scenario-based stochastic optimization.

On the other hand, game theory approaches have recently raised a substantial interest in DR programs [9], [10] . In [11], the optimum solution for time-of-use electricity price was investigated by using a game theory for activating DR in end users. A Stackelberg game was used in [12] for modeling the power exchange between supplier and consumer to achieve the best electricity price for enticing the consumers to adjust their load demand.

The main contribution of this paper is proposing a Stackelberg game-based model to handle the problem between the aggregator, acting as a leader, and consumers, being as followers. The aggregator owns a wind power plant and seeks to maximize the utilization of wind power by giving a bonus to the consumers. On the other hand, the consumers strive to maximize the bonus gained from the aggregator. A well-developed model has been considered for the HVAC systems, and each consumer can adjust its power to increase the deployment of generated wind power. Furthermore, to address the uncertainty in the problem, 20 different scenarios, five scenarios for wind and four scenarios for critical demand, have been considered.

The rest of this paper is organized as follows. Section II presents the system model, including the aggregator and consumers' models. Section III shows the problem formulation of the suggested approach. The simulation results are provided in Section IV. The paper is concluded In Section V.

II. SYSTEM MODEL

A. Consumer Model

It is assumed that each consumer has two types of load, namely non-HVAC (critical load) and HVAC loads. For the former, there is no control by the consumers on the load, while the HVAC load demand can be adjusted for the DR purpose. It is also supposed that each house is equipped with an energy management system which handle the bonus and change the HVAC load. The HVAC system constitutes a large portion of power consumption and thus can affect the load profile to a great extent. In this work, a two-capacity model with the specification shown in Table I is used for simulating the HVAC system [13].

TABLE I.
THERMAL PARAMETERS RELATED TO HOUSES AND HVAC SYSTEMS

Parameter	Value
H_y, H_x, H_g, H_e, H_m	0.33, 0.48, 0.05, 0.29, 5.16 (W/C°-m2)
C_a, C_m	13.02, 112.13, (kJ/C°-m²)
T^x	18 C⁰
$P^{hvac,max}$	8 kWh
$Q^{hvac,min}$, $Q^{hvac,max}$	0, 7.5 kWh
η^c,η^d	0.95
SoC_{min}, SoC_{min}	30-3750 (Wh)

Suppose that $\Delta P = [\Delta P_{n,t}^{hvac}]\ \forall n \in N, \forall t \in T$ and $bonus_{n,t} = [b|\Delta P_{n,t}^{hvac}|]: \forall n \in N, \forall t \in T$ be the strategy set of each consumer and aggregator, respectively, to indicate the power variation of HVAC and bonus given to consumers, in turn. π_{sc} and π_{sw} are the probability of each scenario for the non-HVAC load and wind power, respectively, which are considered to be equiprobable. Hence, the objective function for consumers should to maximize the receiving bonus as (1).

$$\max \sum_{sc=1}^{SC}\sum_{sw=1}^{SW}\sum_{n=1}^{N}\sum_{t=1}^{T}\pi_{sc}\pi_{sw}\left|\Delta P_{sc,sw,n,t}^{hvac}\right| bonus_{sc,sw,n,t} \tag{1}$$

B. Aggregator Model

The aggregator owns a wind farm, and its power can be calculated as follows [6].

$$P^{w} = \begin{cases} a.w_{w} + K, & w_{c} < \forall w_{w} \ \ and \ \ w_{r} > w_{w} \\ P_{r} & w_{w} > w_{r} \end{cases} \tag{2}$$

$$a = P_{r} \big/ w_{r} - w_{c} \tag{3}$$

$$K = -a.w_{c} \tag{4}$$

where Pw and Pr are the wind-generated power and rated power, respectively; wc is the cut-in speed for wind turbine (m/s), wr is the wind speed at rated power (m/s), w_w is the wind speed (m/s), K is a constant value, and α is the slope.

In this model, it is assumed that the aggregator works in favor of the independent system operator (ISO) and thereby its objective is to maximize the utilization of forecasted wind power production while minimizing the amount of bonus given to consumers, as (5).

$$\min \sum_{sc=1}^{SC}\sum_{sw=1}^{SW}\pi_{sc}\pi_{sw}\left(\sum_{t=1}^{T}\left|\sum_{n=1}^{N}P_{sc,n,t}^{cr}+P_{0_{n,t}}^{hvac}+\Delta P_{sc,sw,n,t}^{hvac}-P_{sw,t}^{w}\right| + w\sum_{t=1}^{T}\sum_{n=1}^{N}\left|\Delta P_{sc,sw,n,t}^{hvac}\right| bonus_{sc,sw,n,t}\right) \tag{5}$$

III. PROBLEM FORMULATION

The resulted problem using the Stackelberg game rules is a non-linear bilevel programming model. The aggregator and consumers problems are at the upper-level and the lower-level, respectively. The duality theorem is applied in this paper to recast the bilevel problem into a single level [14]. In this way, the lower-level problem can be substituted by the strong duality, primal feasibility, and dual feasibility constraints. After applying the aforementioned alteration and transforming the absolute value and the quadratic terms into linearized forms, the following problem is yielded.

$$\min \sum_{sc=1}^{SC}\sum_{sw=1}^{SW}\pi_{sc}\pi_{sw}\left(\sum_{t=1}^{T}f_{sc,sw,t}+b\sum_{t=1}^{T}\sum_{n=1}^{N}\left(\sum_{y^{+}=1}^{Y^{+}}m_{y^{+},n,t}^{+}\delta P_{y^{+},sc,sw,n,t}^{hvac+} + \sum_{y^{-}=1}^{Y^{-}}m_{y^{-},n,t}^{-}\delta P_{y^{-},sc,sw,n,t}^{hvac-} + 2\sum_{y^{+}=1}^{Y^{+}}\sum_{y^{-}=1}^{Y^{-}}w_{y^{+},y^{-},sc,sw,n,t}\right)\right) \tag{6}$$

subject to:

$$-f_{sc,sw,t} \le \sum_{n=1}^{N}P_{sc,n,t}^{cr}+P_{0_{n,t}}^{hvac}+(\Delta P_{sc,sw,n,t}^{hvac+}-\Delta P_{sc,sw,n,t}^{hvac-}) - P_{sw,t}^{w} \le f_{sc,sw,t};\ \ \forall sc\in SC, \forall sw \in SW, \forall t\in T \tag{7}$$

$$\left|\Delta P_{sc,sw,n,t}^{hvac}\right| = \Delta P_{sc,sw,n,t}^{hvac+}+\Delta P_{sc,sw,n,t}^{hvac-};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{8}$$

$$\Delta P_{sc,sw,n,t}^{hvac} = \Delta P_{sc,sw,n,t}^{hvac+}-\Delta P_{sc,sw,n,t}^{hvac-};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{9}$$

$$0\le\delta P_{y^{+},sc,sw,n,t}^{hvac+}\le\Delta P_{n}^{hvac\_max}\big/Y^{+};\forall sc\in SC,\forall sw\in SW,\forall y\in Y,\forall n\in N,\forall t\in T \tag{10}$$

$$0\le\delta P_{y^{-},sc,sw,n,t}^{hvac-}\le\Delta P_{n}^{hvac\_max}\big/Y^{-};\forall sc\in SC,\forall sw\in SW,\forall y\in Y,\forall n\in N,\forall t\in T \tag{11}$$

$$m_{y^{+},n,t}^{+}=(2y^{+}-1)\Delta P_{n}^{hvac\_max}\big/Y^{+};\forall y^{+}\in Y^{+},\forall n\in N,\forall t\in T \tag{12}$$

$$m_{y^{-},n,t}^{-}=(2y^{-}-1)\Delta P_{n}^{hvac\_max}\big/Y^{-};\forall y^{-}\in Y^{-},\forall n\in N,\forall t\in T \tag{13}$$

$$\Delta P_{sc,sw,n,t}^{hvac+}=\sum_{y^{+}=1}^{Y^{+}}\delta P_{y^{+},sc,sw,n,t}^{hvac+};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{14}$$

$$\Delta P_{sc,sw,n,t}^{hvac-}=\sum_{y^{-}=1}^{Y^{-}}\delta P_{y^{-},sc,sw,n,t}^{hvac-};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{15}$$

$$(\Delta P_{sc,sw,n,t}^{hvac+})^{2}=\sum_{y^{+}=1}^{Y^{+}}m_{y^{+},n,t}^{+}\delta P_{y^{+},sc,sw,n,t}^{hvac+};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{16}$$

$$(\Delta P_{sc,sw,n,t}^{hvac-})^{2}=\sum_{y^{-}=1}^{Y^{-}}m_{y^{-},n,t}^{-}\delta P_{y^{-},sc,sw,n,t}^{hvac-};\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{17}$$

$$w_{y^{+},y^{-},sc,sw,n,t}\ge 0;\forall y^{+}\in Y^{+},\forall y^{-}\in Y^{-},\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{18}$$

$$w_{y^{+},y^{-},sc,sw,n,t}\ge\Delta P_{n}^{hvac\_max}\delta P_{y^{-},sc,sw,n,t}^{hvac-}\big/Y^{-}+\Delta P_{n}^{hvac\_max}\delta P_{y^{+},sc,sw,n,t}^{hvac+}\big/Y^{+} -(\Delta P_{n}^{hvac\_max})^{2}\big/Y^{+}Y^{-};\forall sc\in SC,\forall sw\in SW,\forall y^{+}\in Y^{+},\forall y^{-}\in Y^{-},\forall n\in N,\forall t\in T \tag{19}$$

$$w_{y^{+},y^{-},sc,sw,n,t}\le\Delta P_{n}^{hvac\_max}\delta P_{y^{+},sc,sw,n,t}^{hvac+}\big/Y^{-};\forall y^{+}\in Y^{+},\forall y^{-}\in Y^{-},\forall sc\in SC,\forall sw\in SW,\forall n\in N,\forall t\in T \tag{20}$$

$$w_{y^+,y^-,sc,sw,n,t} \le \Delta P_n^{hvac\_max} \delta P_{y^+,sc,sw,n,t}^{hvac-} \Big/ Y^+ ; \forall y^+ \in Y^+, \forall y^- \in Y^-, \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (21)$$

$$T_{sc,sw,n,t}^{a} = \frac{T_{sc,sw,n,t-1}^{a} + [H_n^m T_{sc,sw,n,t-1}^{m} + H_n^e T_t^e + H_n^g T_t^g + H_n^x T^x + Q_{sc,sw,n,t}^{hvac}] \big/ c_n^a}{1 + \Delta t (H_n^m + H_n^e + H_n^g + H_n^x) \big/ c_n^a} : (\lambda_{sc,sw,n,t});, \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (22)$$

$$T_{sc,sw,n,t}^{m} = \frac{T_{sc,sw,n,t-1}^{m} + \Delta t [H_n^m T_{sc,sw,n,t-1}^{a} + H_n^y T_t^e] \big/ c_n^m}{1 + \Delta t (H_n^m + H_n^y) \big/ c_n^m} : (\varphi_{sc,sw,n,t}); \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (23)$$

$$T_{n,t}^{set} - \frac{\theta}{2} \le T_{sc,sw,n,t}^{a} \le T_{n,t}^{set} + \frac{\theta}{2} : (\beta_{sc,sw,n,t}^{lo}, \beta_{sc,sw,n,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (24)$$

$$SoC_{sc,sw,n,t} = SoC_{sc,sw,n,t-1} + \left(\eta^c (P_{0_{n,t}}^{hvac} + \Delta P_{sc,sw,n,t}^{hvac}) - Q_{sc,sw,n,t}^{hvac} \Big/ \eta^d\right) - \xi_{sc,sw,n,t-1} : (\alpha_{sc,sw,n,t}); \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (25)$$

$$SoC_{n,t}^{\min} \le SoC_{sc,sw,n,t} \le SoC_{n,t}^{\max} : (\mu_{sc,sw,n,t}^{lo}, \mu_{sc,sw,n,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (26)$$

$$\xi_{sc,sw,n,t} = \eta_n . SoC_{sc,sw,n,t} : (\sigma_{sc,sw,n,t}); \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (27)$$

$$\Delta P_n^{hvac-\min} \le \Delta P_{sc,sw,n,t}^{hvac} \le \Delta P_n^{hvac-max} : (\iota_{sc,sw,n,t}^{lo}, \iota_{sc,sw,n,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (28)$$

$$0 \le \Delta P_{sc,sw,n,t}^{hvac} \le P_n^{hvac\_max} - P_{0_{n,t}}^{hvac} : (\nu_{sc,sw,n,t}^{lo}, \nu_{sc,sw,n,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (29)$$

$$\left|\Delta P_{sc,sw,n,t}^{hvac}\right| \le \Delta P_n^{hvac\_max} : (\rho_{sc,sw,n,t}); \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (30)$$

$$\left|\sum_{n=1}^{N} P_{sc,n,t}^{cr} + P_{0_{n,t}}^{hvac} + \Delta P_{sc,sw,n,t}^{hvac} - P_{sw,t}^{w}\right| \le \left|\sum_{n=1}^{N} P_{sc,n,t}^{cr} + P_{0_{n,t}}^{hvac} - P_{sw,t}^{w}\right| : (\upsilon_{sc,sw,t}^{lo}, \upsilon_{sc,sw,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall t \in T \quad (31)$$

$$\sum_{t=1}^{T} \Delta P_{sc,sw,n,t}^{hvac} = 0 : (\varepsilon_{sc,sw,n,t}); \forall sc \in SC, \forall sw \in SW, \forall n \in N \quad (32)$$

$$Q_n^{hvac-\min} \le Q_{sc,sw,n,t}^{hvac} \le Q_n^{hvac-max} : (\delta_{sc,sw,n,t}^{lo}, \delta_{sc,sw,n,t}^{up}); \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (33)$$

$$-\eta^c \alpha_{sc,sw,n,t} + \iota_{sc,sw,n,t}^{lo} + \iota_{sc,sw,n,t}^{up} + \nu_{sc,sw,n,t}^{lo} + \nu_{sc,sw,n,t}^{up} + \rho_{sc,sw,n,t} + \varepsilon_{sc,sw,n,t} + \upsilon_{sc,sw,t}^{lo} + \upsilon_{sc,sw,t}^{up} = bonus_{sc,sw,n,t}; \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (35)$$

$$\eta^c \alpha_{sc,sw,n,t} - \iota_{sc,sw,n,t}^{lo} - \iota_{sc,sw,n,t}^{up} - \nu_{sc,sw,n,t}^{lo} - \nu_{sc,sw,n,t}^{up} + \rho_{sc,sw,n,t} - \varepsilon_{sc,sw,n,t} - \upsilon_{sc,sw,t}^{lo} - \upsilon_{sc,sw,t}^{up} = bonus_{sc,sw,n,t}; \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (36)$$

$$\alpha_{sc,sw,n,t} - \alpha_{sc,sw,n,t+1} + \mu_{sc,sw,n,t}^{lo} + \mu_{sc,sw,n,t}^{up} - \eta_{sc,sw,n} \sigma_{sc,sw,n,t} = 0; \forall sc \in SC, \forall sw \in SW, \forall t = 1...T-1, \forall n \in N \quad (37)$$

$$\alpha_{sc,sw,n,T} + \mu_{sc,sw,n,T}^{lo} + \mu_{sc,sw,n,T}^{up} - \eta_n \sigma_{sc,sw,n,T} = 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N \quad (38)$$

$$\lambda_{sc,sw,n,t} - \frac{1}{1 + [H_n^m + H_n^e + H_n^g + H_n^x] \big/ c_n^a} \lambda_{sc,sw,n,t+1} + \beta_{sc,sw,n,t}^{lo} + \beta_{sc,sw,n,t}^{up} - \frac{H_n^m \big/ c_n^m}{1 + (H_n^m + H_n^y) \big/ c_n^m} \varphi_{sc,sw,n,t+1} = 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t = 1..T-1 \quad (39)$$

$$\lambda_{sc,sw,n,T} + \beta_{sc,sw,n,T}^{lo} + \beta_{sc,sw,n,T}^{up} = 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N \quad (40)$$

$$\frac{-\lambda_{sc,sw,n,t} \big/ c_n^a}{1 + [H_n^m + H_n^e + H_n^g + H_n^x] \big/ c_n^a} + \frac{1}{\eta^d} \alpha_{sc,sw,n,t} + \delta_{sc,sw,n,t}^{lo} + \delta_{sc,sw,n,t}^{up} = 0; \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (41)$$

$$-\frac{H_n^m \big/ c_n^a}{1 + [H_n^m + H_n^e + H_n^g + H_n^x] \big/ c_n^a} \lambda_{sc,sw,n,t+1} - \frac{1}{1 + (H_n^m + H_n^y) \big/ c_n^m} \varphi_{sc,sw,n,t+1} + \varphi_{sc,sw,n,t} = 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t = 1..T-1 \quad (42)$$

$$\varphi_{sc,sw,n,T} = 0; \ \forall sc \in SC, \forall sw \in SW, \forall n \in N \quad (43)$$

$$\alpha_{sc,sw,n,t+1} + \sigma_{sc,sw,n,t} = 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t = 1...T \quad (44)$$

$$\sigma_{sc,sw,n,T} = 0 \ ; \forall sc \in SC, \forall sw \in SW, \forall n \in N \quad (45)$$

$$\beta_{sc,sw,n,t}^{lo} \le 0, \beta_{sc,sw,n,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (46)$$

$$\mu_{sc,sw,n,t}^{lo} \le 0, \mu_{sc,sw,n,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (47)$$

$$\iota_{sc,sw,n,t}^{lo} \le 0, \iota_{sc,sw,n,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (48)$$

$$\nu_{sc,sw,n,t}^{lo} \le 0, \nu_{sc,sw,n,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (49)$$

$$\delta_{sc,sw,n,t}^{lo} \le 0, \delta_{sc,sw,n,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall t \in T, \forall n \in N \quad (49)$$

$$\rho_{sc,sw,n,t} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall n \in N, \forall t \in T \quad (50)$$

$$\upsilon_{sc,sw,t}^{lo} \le 0, \upsilon_{sc,sw,t}^{up} \ge 0; \forall sc \in SC, \forall sw \in SW, \forall t \in T \quad (51)$$

$$\sum_{sc=1}^{SC} \sum_{sw=1}^{SW} \pi_{sc} \pi_{sw} b \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{y^+=1}^{Y^+} m_{y^+,n,t}^{+} \delta P_{y^+,sc,sw,n,t}^{hvac+} + \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{y^-=1}^{Y^-} m_{y^-,n,t}^{-} \delta P_{y^-,sc,sw,n,t}^{hvac-} + 2 \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{y^+=1}^{Y^+} \sum_{y^-=1}^{Y^-} w_{y^+,y^-,sc,sw,n,t} =$$

$$\sum_{n=1}^{N} \sum_{t=1}^{T} \left(\begin{aligned} & \beta_{sc,sw,n,t}^{lo} (T_{n,t}^{set} - \tfrac{\theta}{2}) + \beta_{sc,swn,t}^{up} (T_{n,t}^{set} + \tfrac{\theta}{2}) + \\ & \mu_{sc,sw,n,t}^{lo} SoC_{n,t}^{\min} + \mu_{,sc,sw,n,t}^{up} SoC_{n,t}^{\max} - \iota_{sc,sw,n,t}^{lo} \Delta P_n^{hvac\_\max} \\ & + \iota_{sc,sw,n,t}^{up} \Delta P_n^{hvac\_\max} + \nu_{sc,sw,n,t}^{up} (P_n^{hvac\_\max} - P_{0_{n,t}}^{hvac}) \\ & + \rho_{sc,sw,n,t} . \Delta P_n^{hvac\_\max} - \delta_{sc,sw,n,t}^{lo} Q_n^{hvac\_\max} \\ & + \delta_{sc,sw,n,t}^{up} Q_n^{hvac\_\max} \end{aligned} \right)$$

$$+ \sum_{n=1}^{N} \lambda_{sc,sw,n,1} \frac{T_{sc,sw,n,0}^{a} + [H_n^m T_{sc,sw,n,0}^{m} + H_n^e T_1^e + H_n^g T_1^g + H_n^x T^x] \big/ c_n^a}{1 + [H_n^m + H_n^e + H_n^g + H_n^x] \big/ c_n^a}$$

$$+ \sum_{n=1}^{N} \sum_{t=2}^{T} \lambda_{sc,sw,n,t} \frac{\frac{1}{c_n^a} [H_n^e T_t^e + H_n^g T_t^g + H_n^x T^x]}{1 + \frac{1}{c_n^a} [H_n^m + H_n^e + H_n^g + H_n^x]} + \sum_{n=1}^{N} \varphi_{sc,sw,n,1}$$

$$\frac{T_{sc,sw,n,0}^{m} + \frac{1}{c_n^m} [H_n^m T_{sc,sw,n,0}^{a} + H_n^y T_1^e]}{1 + \frac{1}{c_n^m} [H_n^m + H_n^y]} + \sum_{n=1}^{N} \sum_{t=2}^{T} \varphi_{sc,sw,n,t} \frac{\frac{1}{c_n^m} [H_n^y T_t^e]}{1 + \frac{1}{c_n^m} [H_n^m + H_n^y]}$$

$$+ \sum_{n=1}^{N} \alpha_{sc,sw,n,1} (SoC_{n,0} + \eta^c P_{0_{n,0}}^{hvac} - \xi_{n,0}) + \sum_{n=1}^{N} \sum_{t=2}^{T} \alpha_{n,t} \eta^c P_{0_{n,0}}^{hvac}$$

where (6) is the linearized form of (5), and for this reason, (7)-(21) are added to the problem. (7) is used to linearize the absolute value included in the first term of (5). (8) and (9) are for linearization of the second term of (5), while (10)-(17) and (18)-(21) are adopted to linearize the quadratic terms $\Delta P_{sc,sw,n,t}^{hvac+\ 2}$, $\Delta P_{sc,sw,n,t}^{hvac-\ 2}$ and the product $\Delta P_{sc,sw,n,t}^{hvac-} . \Delta P_{sc,sw,n,t}^{hvac+}$, respectively; $m_{y+,n,t}^{+}$ and $m_{y-,n,t}^{-}$ stand for the slopes of the HVAC power variation related to the y$_{th}$ block, whereas Y^- and Y^+ are the number of the blocks; $\delta_{y+,n,t}^{hvac+}$, $\delta_{y-,n,t}^{hvac-}$, indicate the largest size for each slope;

interested readers may refer to [15] for more information. The primal and dual feasibility constraints are shown in (22)-(32) (related to the HVAC system), and (34)-(50), respectively. the strong duality equilibrium is also presented in (51). sc, sw, n, and t are indices related to the scenarios for consumers' non-HVAC load, scenarios for wind-generated power, consumers, and time, respectively. $H_e, H_y, H_m, H_x, \theta, P^{hvac,max}, P^{hvac,min}$, SoC^{max}, $SoC^{min}, Q^{hvac,max}, Q^{hvac,min}, C_a, C_m, T^{set}, \eta^C, \eta^d$, and η_n are parameters of HVAC. $P^{hvac}_{sc,sw,n,t}, Q^{hvac}_{sc,sw,n,t}, T^{a}_{sc,sw,n,t}$, $T^{m}_{sc,sw,n,t}, SoC_{sc,sw,n,t}$, and $\mathcal{E}_{sc,sw,n,t}$ are variables of the HVAC, see [13] for more information. $P^{w}_{sw,t}$ shows the wind power generation. $\lambda_{sc,sw,n,t}, \varphi_{sc,sw,n,t}, \rho_{sc,sw,n,t}, \sigma_{sc,sw,n,t}, \varepsilon_{sc,sw,n,t}$, $\alpha_{sc,sw,n,t}, \beta^{lo}_{sc,sw,n,t}, \mu^{lo}_{sc,sw,n,t}, \delta^{lo}_{sc,sw,n,t}, \iota^{lo}_{sc,sw,n,t}, \nu^{lo}_{sc,sw,n,t}, \upsilon^{lo}_{sc,sw,t}$, $\beta^{up}_{sc,sw,n,t}, \mu^{up}_{sc,sw,n,t}, \delta^{up}_{sc,sw,n,t}, \iota^{up}_{sc,sw,n,t}, \nu^{up}_{sc,sw,n,t}$, $\upsilon^{up}_{sc,sw,t}$ stand for dual variables.

IV. SIMULATION RESULTS

In the case study, one day with 24 steps (hours) has been considered for the simulation. It is assumed that there are five houses and one aggregator. Two different case studies are conducted. in Case 1, there is no control on the HVAC system, and the indoor temperature has been set to 21, 21, 20, 22, and 20 Celsius for Houses 1, 2, 3, 4, and 5, respectively, while for Case 2, which presents the proposed approach, HVAC system power can be regulated (plus-minus 1000 Watt at maximum for each house and at each hour) to contribute in maximizing the utilization of generated wind power. A plus-minus two degrees deviation from the houses' indoor temperature set points in Case 1 has been considered for Case 2. The problem (6)-(51) is implemented in GAMS and solved by solver CPLEX. Different scenarios, including four scenarios for non-HVAC load (Figure 1) and five scenarios for wind power (Figure 2) is considered which constitute 20 scenarios in total. For the sake of saving space, the simulation result are illustrated only for three scenarios, related to scenario 1 (sc 1 of non-HVAC load and sw 1 of wind power), scenario 9 (sc 3 of non-HVAC load and sw 3 of wind power), scenario 20 (sc 4 of non-HVAC load and sw 5 of wind power), respectively. In Figures 3, 4, and 5, the generated wind power, and the summation of non-HVAC load (critical load) and HVAC load are represented for both Cases 1 and 2. As can be observed in Figures 3, 4, and 5, the deviation between wind power and consumers' demand has substantially decreased using the proposed approach. The indoor temperatures for houses for scenarios 1, 9, and 20 are portrayed in Figures 6, 7, and 8, respectively. As these figures show, the indoor temperature has remained in the specified band for all houses. For example, for house #5, considering the two degrees deviation from the setpoint 20, it will result in a range of 18 to 22 Celsius for the temperature. Regarding the Figures 6, 7, and 8 for scenarios 1, 9, and 20, it is noticeable that the temperature for house #5 has been kept between 18 and 22, which shows the validity of the proposed method. In addition, Figure 9 illustrates the total amount of bonus which the aggregator gives to all the consumers for motivating them into adjusting their load profile. As it is obvious from this figure, where the deviation between wind and consumption is high, the aggregator is willing to dedicate more bonus to entice consumers for changing their load. For example in scenario 1, as it can be perceived in Figure 3, this deviation is relatively higher in hours 7, 12, 16, 19, and 20 rather than other hours. Therefore, the aggregator offered more bonus to the consumers in these hours (see Fig. 3), and accordingly, the consumers have changed their consumption, and the deviation decreased. Consequently, the Stackelberg game ensured a fair interaction between the aggregator and consumers and resulted in a solution that serves best both the players.

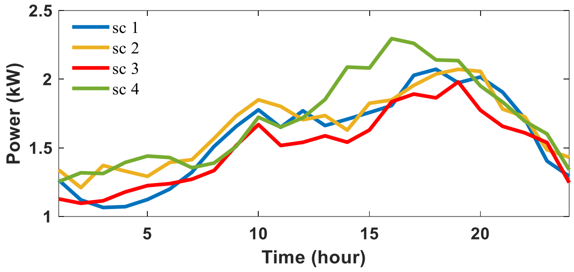

Fig. 1. Different scenarios for non-HVAC loads of consumers

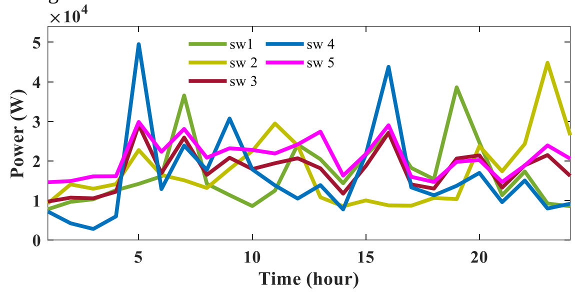

Fig. 2. Different scenarios for wind farm

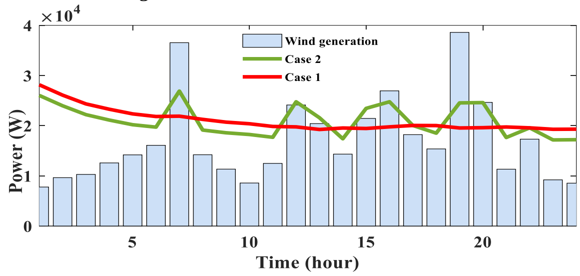

Fig. 3. Wind power and the total load of consumers (scenario1)

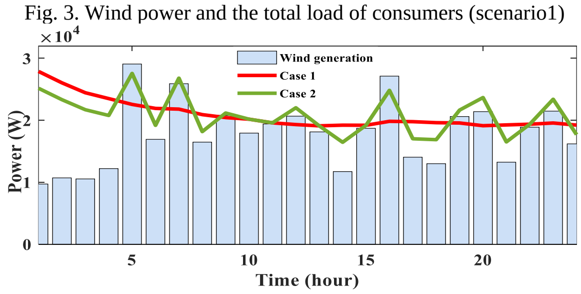

Fig. 4. Wind power and the total load of consumers (scenario9)

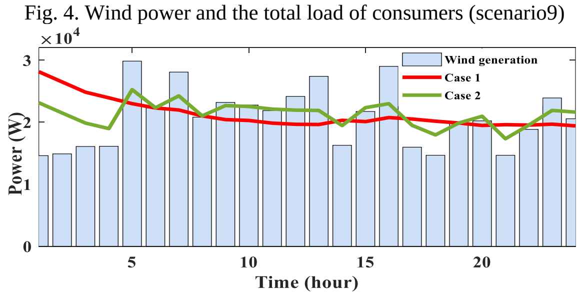

Fig. 5. Wind power and the total load of consumers (scenario20)

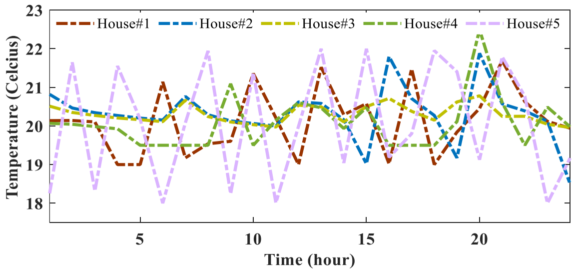

Fig. 6. Indoor temperature (scenario 1)

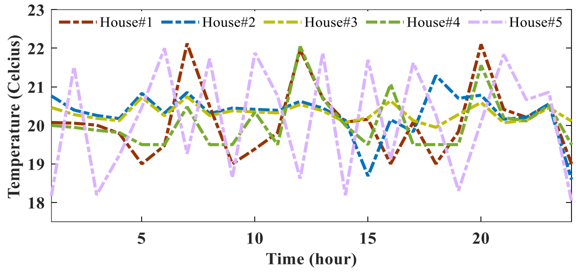

Fig. 7. Indoor temperature (scenario 9)

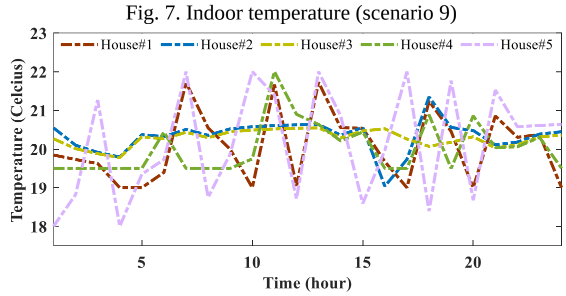

Fig. 8. Indoor temperature (scenario 20)

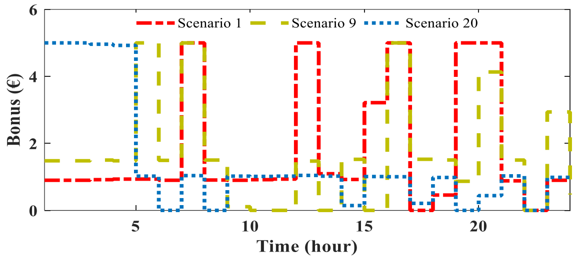

Fig. 9. Total bonus given to all consumers by the aggregator

V. CONCLUSION

In this work, the Stackelberg game theory has been used for considering the interaction between aggregator and consumers. The aggregator, which owns a wind farm is willing to decrease the deviation between generated wind power and load consumption at each hour. For this reason, it gives a bonus to the consumers for changing their load profile based on the forecasted wind power. Subsequently, the consumers change their demand, and the aggregator reacts again based on the new situation. This procedure will keep performing until the game equilibrium solution is revealed. In this paper, the strong duality theorem has been used to recast the resulted bilevel problem into a single-level one to facilitate the frustrating iterative process. Finally, as the simulation results demonstrate, the deployment of wind power, which was the primary objective of the aggregator, has been extensively improved. On the other hand, the consumers receive a bonus for their contribution while maintaining their comfort level by keeping the indoor temperature in a desired band.

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