Response to Reviewer#2

Reviewer#2: This paper is dealing with A Demand Response Transaction Method for Integrated Energy Systems with Trigonometric Membership Function Based 3 Uncertainty Model of Costumers' Responsive Behaviors. The man concept is related to the demand response and the transaction methods within the IESs. The topic is timely and interesting, however, there are some comments before more consideration in this journal.

Thanks to the reviewer for the comments and the valuable suggestions on the overall manuscript. Based on your comments, we have made corresponding amendments to the paper. Kindly find our responses to each of your comments and related modifications below.

Reviewer#2, Concern # 1: Please provide some quantitative achievements in the Abstract.

Author response:

Thanks to the reviewer for the comments and valuable suggestions.

This paper focuses on the uncertainty of the excitation-type flexible load response and proposed a decentralized DR transaction model for the customers to actively interact with the IES. Firstly, the uncertainty problem of the incentive-based DR method is studied. The relationship between the uncertainty level of user response and the incentive level has been pointed out. Secondly, fuzzy variables are used to represent user response; then, the trigonometric membership fuzzy function is used to construct the uncertainty model of flexible load response. Finally, the transaction model containing fuzzy variables is trans-formed into a deterministic model for a solution. In the case study, the impact of the uncertainty of user response volume on the revenue of each transaction entity and the impact of the fuzzy chance constraint confidence level on the response revenue are investigated. The results show that the revenue of each transaction entity decreases to a certain extent under the consideration of the uncertainty of user response volume; the social welfare of the whole transaction increases as the confidence level of the chance constraint chang-es from high to low.

In line with the recommendations, we have listed some quantifiable achievements analysis in the Abstract.

Details of the revision are available in **Author action.**

Author action:

The Abstract is modified as follows:

As an important regulation tool for power systems, demand response can greatly improve system flexibility and economy. However, when an integrated energy system with a large number of flexible loads is aggregated for demand response transaction, the uncertainty in the amount of load response should be taken into account. Therefore, a demand response transaction model for an integrated energy system that considers the uncertainty of customer demand response is proposed in this paper. At first, the uncertainty of incentive-based demand response is analyzed, and the relationship

between the incentive level and the fluctuation of customer response volume is investigated. The flexible loads are classified into curtailable loads, translatable loads, and replaceable loads. Secondly, fuzzy variables are used to represent the response volume of users. After that, a trigonometric membership function is used to represent the degree of uncertainty in the response volume of different flexible loads. Finally, the objective functions and chance constraints containing fuzzy variables are converted into explicit equivalence classes for solving. In the case study, the impact of the uncertainty of user response volume on the revenue of each transaction entity and the impact of the fuzzy chance constraint confidence level on the response revenue are investigated. The results show that the revenue of each transaction entity decreases to a certain extent under the consideration of the uncertainty of user response volume; the social welfare of the whole transaction increases as the confidence level of the chance constraint changes from high to low

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Reviewer#2, Concern # 2: Regarding the Translatable loads, how do the Authors guarantee the consumption during the operating horizon? Please refer to 'A two-stage joint operation and planning model for sizing and siting of electrical energy storage devices considering demand response programs, Equations 26-29 can be helpful.

Author response:

Thanks to the reviewer for the valuable comment. In our previous manuscript, the constraints to guarantee the consumption of the translatable loads during the operating horizon are neglected due to our poor understanding of this type of load. Through deeply reading the reference [1], we added these constraints to our model.

$$\left|P_i^t - P_i^{t-1}\right| \le \gamma \tag{1}$$

where the parameter, γ, in (1) represents the inclination of aggregators to alter their demand from one hour to another.

Details of the revision are available in **Author action.**

Involved references:

[1] M. S. Javadi et al., “A two-stage joint operation and planning model for sizing and siting of electrical energy storage devices considering demand response programs,” International Journal of Electrical Power & Energy Systems, vol. 138, p. 107912, Jun. 2022, doi: 10.1016/j.ijepes.2021.107912.

Author action:

2.2. Constraints

This section uses a fuzzy chance constraint to represent the constraint [23], allowing the established constraint to be unsatisfied to some extent, but the confidence that the constraint holds should be no less than a pre-given confidence level.

Based on the above theory, the expressions for the load reserve constraint, the maximum customer response constraint, and the common constraint for different loads are shown below. The load

reserve constraint indicates that the grid needs to allow sufficient standby capacity to solve the customer's uncertain response problem and ensure stable system operation.

$$Cr\{\sum_{i=1}^{n_{cu}}\Delta\tilde{P}_i^{cu}(t)+\sum_{i=1}^{n_{tran}}\Delta\tilde{P}_i^{tran}(t)+\sum_{i=1}^{n_{trans}}\Delta\tilde{P}_i^{trans}(t)+\sum_{i=1}^{n_{re}}\Delta\tilde{P}_i^{re}(t)\geq(1-\delta_{dr})P_{\min}^{dr}(t)\}\geq\beta_1$$

(2)

$$Cr\{\sum_{i=1}^{n_{cu}}\Delta\tilde{P}_i^{cu}(t)+\sum_{i=1}^{n_{tran}}\Delta\tilde{P}_i^{tran}(t)+\sum_{i=1}^{n_{trans}}\Delta\tilde{P}_i^{trans}(t)+\sum_{i=1}^{n_{re}}\Delta\tilde{P}_i^{re}(t)\leq P_{dr,\max}^{adlo}(t)\}\geq\beta_2$$

(3)

where $Cr\{\}$ is the expression for the confidence level; δ_{dr} represents the standby capacity factor of the grid and satisfies $\delta_{dr}\in[0,1]$, β_1 represents the confidence level that the system standby constraint holds; and β_2 represents the confidence level that the maximum user response volume constraint holds. The confidence levels that should be satisfied for multiple fuzzy chance constraints are generally considered to be the same.

For curtailable loads, the following constraints shall be met

$$\varepsilon_{i,\min}^{cu}(t)\leq\varepsilon_i^{cu}(t)\leq\varepsilon_{i,\max}^{cu}(t) \quad (4)$$

$$\sum_{t=1}^{T}\mu_i^{cu}(t)\leq N_{c,i}^{\max} \quad (5)$$

$$\sum_{t}^{t+t_{\min}^{cu}-1}\mu_i^{cu}(t)\geq t_{\min}^{cu}(\mu_i^{cu}(t)-\mu_i^{cu}(t-1)) \quad (6)$$

$$\sum_{t}^{t+t_{\max}^{cu}}(1-\mu_i^{cu}(t))\geq 1 \quad (7)$$

$$\left|\Delta P_i^{cu}(t)-\Delta P_i^{cu}(t-1)\right|\leq v_{\max}^{l} \quad (8)$$

where $\varepsilon_{i,min}^{cu}(t)$ represents the minimum cut rate of the curtailable load; t_{min}^{cu} represents the minimum continuous cut response time; t_{max}^{cu} represents the maximum continuous cut response time; $N_{c,i}^{max}$ represents the maximum time of load cuts allowed in a dispatch cycle; v_{max}^{l} represents the maximum load cut rate allowed by the curtailable load; T represents the entire response time. Equation **Error! Reference source not found.** limits the response volume of the curtailable load. Equation **Error! Reference source not found.** limits the maximum number of participants in the DR. Equations **Error! Reference source not found.Error! Reference source not found.** represent continuous load response constraint, and the equation **Error! Reference source not found.** is the load response speed constraint.

For translatable loads, the following constraints shall be met

$$\lambda_{i,\min}^{tran}(t)\leq\lambda_i^{tran}(t)\leq\lambda_{i,\max}^{tran}(t) \quad (9)$$

$$\sum_{t}^{t+T_{\min,du}^{tran,i}} \mu_i^{tran}(t) \geq T_{\min,du}^{tran,i}(\mu_i^{tran}(t) - \mu_i^{tran}(t-1)), t \in [t_r^{st}, t_r^{en} - T_{\min,du}^{tran,i} + 1]$$

(10)

$$\sum_{t=t_b^{st}}^{t_b^{en}} \Delta P_i^{tran}(t) = \sum_{t=t_{ola}^{st}}^{t_{ola}^{en}} \Delta P_{i,a}^{tran}(t) \quad (11)$$

$$\sum_{t_{af}^{st} \in i)_{st}^{trans,i}} \mu_{t_{af}^{st}}^{trans,i} \leq 1 \quad (12)$$

where $\lambda_{i,min}^{tran}(t)$, $\lambda_{i,max}^{tran}(t)$ represents the minimum load translate rate and maximum load translate rate respectively; $T_{min,du}^{tran,i}$ represents the minimum duration of translatable load; $\Delta P_{i,a}^{tran}(t)$ represents transferable load power after response. Equation (9) limits the load translate rate, Equation (10) limits the duration of translatable load, Equation (11) ensures the balance of the response volumes.

For replaceable loads, the electrical energy substitution rates should satisfy the following constraints:

$$\mu_{i,\min}^{re}(t) \leq \mu_i^{re}(t) \leq \mu_{i,\max}^{re}(t) \quad (13)$$

where $\mu_{i,min}^{re}(t)$ and $\mu_{i,max}^{re}(t)$ represent the minimum and maximum electrical energy substitution rates for replaceable loads, respectively.

The grid operator transaction model constraints are shown below:

$$P_{dr}(t) \geq P_{\min}^{dr}(t) \quad (14)$$

$$C_{price,\min}^{n}(t) \leq C_{price}^{n}(t) \leq C_{price,\max}^{n}(t), n = cu, tran, trans, re \quad (15)$$

where $P_{min}^{dr}(t)$ represents the minimum DR capacity required by the grid at time t; $C_{price,min}^{n}(t)$, $C_{price,max}^{n}(t)$ are the minimum and maximum unit response capacity offered by the grid operator to the VPP at time t, respectively. Equation (14) limits the minimum of DR volumes, Equation (15) limits the transaction cost of different loads.

VPP operator transaction model constraints:

$$C_{vpp}(t) \leq C_{\max}^{vpp}(t) \quad (16)$$

$$P_{dr}^{adlo}(t) = \sum_{i=1}^{n_{cu}} \Delta P_i^{cu}(t) + \sum_{i=1}^{n_{tran}} \Delta P_i^{tran}(t) + \sum_{i=1}^{n_{trans}} \Delta P_i^{trans}(t) + \sum_{i=1}^{n_{re}} \Delta P_i^{re}(t)$$

(17)

$$P_{dr}(t) = P_{dr}^{adlo}(t) \quad (18)$$

$$P_{dr}^{adlo}(t) \leq P_{dr,\max}^{adlo}(t) \quad (19)$$

$$\left| P_i^t - P_i^{t-1} \right| \leq \gamma \quad (20)$$

where $C_{max}^{vpp}(t)$ represents the maximum transaction cost of the VPP operator; $P_{dr}^{adlo}(t)$ is the DR capacity provided by the user; and $P_{dr,max}^{adlo}(t)$ represents the maximum DR capacity that can be provided by the user. Equation (16) limits the maximum transaction cost of the VPP operator. Equations (17)-(18) ensure the balance of the transaction volumes. Equation (19) limits the maximum DR volumes of the VPP operator. The parameter, γ, in (1) represents the inclination of aggregators to alter their demand from one period to another [24].

Reviewer#2, Concern # 3: The Literature Review can be extended. There are some good Review Papers that can help the Authors to conduct a comprehensive literature review. Please see Demand response programs in multi-energy systems: A review, which is recently published by the same publisher.

Author response:

Thank you for your valuable comments. According to your suggestion, we have extended the content of the literature review, especially including the DR in the IES and the uncertainty modeling methods. Importantly, we added the reference [1] to emphasize the role of DR in the IES.

The development of an IES should consider safety, economy, and cleanliness. It integrates various energy resources such as natural gas and photovoltaic power in the region and meets the multiple energy requirements of users. Thus the IES is becoming a hot spot for research in the energy field.

With the development of IES, technological advances in DR have become a key solution to achieve this energy transition. DR can effectively increase the active participation of consumers in the IES [1].

Incentive-based DR strategies are a very effective way of involving flexible loads in the grid DR process. Yet, for IESs that aggregate a large number of flexible loads, there exists uncertainty in the response volume they provide to the grid because of the specificity of the way it aggregate resources.

In our paper, we propose a DR transaction model for the customers to actively interact with the IES. Considering that various types of flexible loads with different responsive potentials and uncertainty in the customers may influence the transaction results, we apply the fuzzy theory with trigonometric membership-function to describe the uncertainty of these flexible loads.

Involved references:

[1] M. Vahid-Ghavidel, M. S. Javadi, M. Gough, S. F. Santos, M. Shafie-khah, and J. P. S. Catalão, “Demand Response Programs in Multi-Energy Systems: A Review,” Energies, vol. 13, no. 17, p. 4332, Aug. 2020, doi: 10.3390/en13174332.

Details of the revision are available in **Author action.**

Author action:

The development of an integrated energy system (IES) should consider the safety, economy, and cleanliness. It integrates various energy resources such as natural gas and photovoltaic power in the region, and meets the multiple energy requirements of users [1,2]. Thus the IES is becoming a hot spot for research in the energy field[3,4].

With the development of IES, technological advances in demand response (DR) have become a key solution to achieve this energy transition. DR can effectively increase the active participation of consumers in the IES [5]. Flexible loads in IESs have a strong DR capability. Flexible loads on the customer side can adjust their electricity consumption behavior according to the price-based DR mechanism [6][7] and the incentive-based DR mechanism [8], relieving the electricity supply tensions of the IES. Based on multiple types of low carbon factors and price-based DR mechanisms, Ma et al [9] construct an energy efficiency improvement scheduling model with abandoned wind penalty costs, power purchase costs, equipment operation and maintenance costs, and carbon transaction costs as optimization targets, improving the comprehensive energy efficiency of the IES. Yang et al [10] proposed the rolling optimization planning framework and model of IES considering CAES and sliding time window-based electric and heating integrated demand response (IDR), improving the economy and flexibility of the IES. Based on the DR potential and consumer's consumption characteristics, as well as the coupling characteristics of the energy flows in the regionally integrated energy system (RIES), Hu et al.[11] establish a RIES optimization model that considers the DR of cooling, heating and electricity consumption of flexible loads. The synergistic optimization of the supply side and the consumer side is realized.

Incentive-based DR strategies are a very effective way of involving flexible loads in the grid DR process [12]. Du et al. [13] provide an in-depth analysis of incentive-based IDR in an IES model. A customer-side IDR service architecture based on electric heating multi-energy interconnection is designed. Wang et al [14] designed an IDR scheme that takes different types of consumers into account. By designing a price-based mechanism that implements various prices for different consumers, the total cost of user participation in IDR can be reduced. Jiang et al.[15] incorporates consumers' heating and cooling demand into IDR scheduling, then proposes an IDR mechanism with three effective load shedding incentive models. The incentive methods are used to increase heating and cooling loads and increase consumers' motivation. However, in all of the above incentive-based DR studies, the response volume of the flexible load during the transaction is default certain. Yet, for IESs that aggregate a large number of flexible loads, there exists uncertainty in the response volume they provide to the grid because of the specificity of the way it aggregates resources. Also, there are inherent uncertainties such as communication delays, coupled with the fact that the response capacity provided by the user is also highly subjective [16][17]. The response volume is susceptible to a variety of factors such as unexpected next-day conditions, subjective and objective negligence, and changes in consumption behavior [18].

Traditional methods usually transform a certain optimization model into a stochastic optimization via adding random variables with a bounded interval or a certain probability distribution[19,20]. These methods are required to form the accurate probability distribution of every random variable, while there are numerous flexible loads participating in the DR and it is unfeasible to confirm their accurate probability. Thus, a robust-based optimization model is proposed to tackle this problem[21], yet the results solved by this model could be quite conservative along with the poor economy of the system. Considering both the characteristics of flexible loads and the economy of the system, we eventually utilize the fuzzy theory with trigonometric membership-function. Trigonometric membership-functions of uncertain parameters can be obtained by an expert system when a fuzzy number lacks historical information, so this method is of low dependence on historical data and a good description of the uncertainty.

Based on the above problems, this paper focuses on the uncertainty of the excitation-type flexible load response and proposed a DR transaction model for the customers to actively interact with the IES. Firstly, the uncertainty problem of the incentive-based DR method is studied. The relationship between the uncertainty level of user response and the incentive level has been pointed out. Secondly, fuzzy variables are used to represent user response; then, the trigonometric membership fuzzy function is used to construct the uncertainty model of flexible load response. Finally, the transaction model containing fuzzy variables is transformed into a deterministic model for a solution.

The contributions of this paper are threefold：

1) We introduce the analysis of DR uncertainty. Additionally, the DR load uncertainty models of curtailable load, translated load, and replaceable load are proposed respectively.

2) A DR transaction model is investigated. In this model, various types of flexible load response volume uncertainty are taken into consideration.

3) We point out the relationship between the uncertainty level of user response and the incentive level and utilize the trigonometric membership fuzzy function to construct the uncertainty model of flexible load response. Therefore, the transaction model containing fuzzy variables is transformed into a deterministic model for a solution.

The remainder of this paper is arranged as follows. Section Ⅰ introduces the DR load uncertainty analysis and modeling. In Section Ⅱ, a DR transaction model that considers the uncertainty of flexible loads is given. Section Ⅲ elaborates on the process of the model uncertainty. The case study is given in Section Ⅳ to evaluate the impact of the uncertainty of user response volume and the fuzzy chance constraints confidence level on the transaction results of transaction stakeholders. Conclusions are presented in Section Ⅴ.

Reviewer#2, Concern # 4: Term '6. Patents' is not applicable to this work.

Author response:

Thanks to the reviewer for the comment. We carefully check the template of the sustainability and find the mistake we make. we have already deleted Term 6. Patents' in the paper.

Author action:

All the authors proofread the manuscript to correct the mistake exists in the paper.

Reviewer#2, Concern # 5: To highlight the transactions, please clarify whether the concept is centralized or decentralized. In this case, a comprehensive comparison is performed in the Transactive energy framework in multi-carrier energy hubs: A fully decentralized model.

Author response:

Thanks to the reviewer for the comments. In our paper, a DR transaction model for the customers to actively interact with the IES is proposed.

The transaction mode of the proposed method is platform-dominated centralized. In this mode, there are two stakeholders: 1) the grid operator minimizes the operation cost of purchasing DR services from the VPP; 2) the VPP minimizes the total cost for aggregating the flexible loads to participate

in the DR transaction. In response to the reviewer's suggestion, we added a paragraph to highlight the transaction mode of our proposed method. In addition, considering the development of the decentralized model in the transaction, we will further study the transformation of our proposed model into a decentralized model in the future.

Details of the revision are available in **Author action.**

Author action:

DR is increasingly used as an essential regulation tool in power systems, however, when an IES with a large number of flexible loads is aggregated for DR transaction, uncertainty in the amount of load response can have an impact on the process and outcome of the transaction. In this paper, the impact of uncertainty in flexible load response on DR transactions is considered. First, the uncertainty problem of incentive-based DR is analyzed, and the relationship between the level of incentive and the range of fluctuations in the user response volume is investigated. Subsequently, the treatment of uncertainty is introduced, and this paper uses fuzzy variables to represent the user response volume. Based on this, a trigonometric membership function is used to represent the uncertainty level of user response quantity for different types of flexible loads. Finally, for the objective function and chance constraints containing fuzzy variables, they are converted into explicit equivalence classes and then solved. The case study section examines the impact of the uncertainty of user response volume on the revenue of each transaction entity and the impact of the fuzzy chance constraints confidence level on the response revenue. The results demonstrate that the revenue of each transaction entity decreases to a certain extent when the uncertainty of user response volume is considered, and the social welfare of the whole transaction increases as the confidence level of the chance constraint changes from high to low.

The proposed method of dealing with user response uncertainty in this paper provides some ideas and suggestions to solve the problems faced by flexible loads when participating in DR, but it can still be extended in the following two aspects. Firstly, the study of flexible loads response strategy under multiple time scales. The research conducted in this paper does not consider the time scale and does not study the regulation of flexible loads in multiple time scales such as day-ahead, intra-day and real-time. In fact, in the case of approaching time scale, the types of flexible users that can participate in grid DR will be reduced continuously, and the uncertainty of us-er response will also be reduced continuously, even in the real-time stage is possible without considering the problem of user response uncertainty. Secondly, the study of user uncertainty under multiple response mechanisms. In this paper, we only consider the problem of response uncertainty of flexible loads under contract constraints, but in fact, some flexible loads can also participate in the DR of the grid under tariff guidance, and their response uncertainty cannot be ignored.