IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 27, 2021, accepted April 1, 2021, date of publication April 8, 2021, date of current version April 29, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3071879

Premium Power Value-Added Service Product Decision-Making Method Based on Multi-Index Two-Sided Matching

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This work was supported in part by the Research Initiation Fund of Zhejiang Sci-Tech University ''Research on the Premium Power Theory Valuation'' under Grant 19022396-Y, and in part by the National Key Research and Development Plan under Grant 2019YFE0111500.

ABSTRACT With the further reform and development of the electricity retail market in China, the premium power value-added service (PPVS) product is becoming increasingly demanded by high-tech customers. However, the problem of PPVS demand-level matching has not been well studied. How to build an optimal matching and decision-making model which can improve both customers' and electricity retail companies' satisfaction degree is an urgent issue. Thus, this paper proposes a decision-making method for PPVS products with multi-index expectation based on two-sided matching. Firstly, a multi-index evaluation system is established from the perspective of customers and electricity retail companies. Secondly, the loss and gain matrices of customers and electricity retail companies are constructed, considering the difference between the expected level (EL) and the actual level (AL) of the evaluation indices. Thirdly, perceived utility (PU) of both customers and electricity retail companies are described with the introduction of elation function and disappointment function, due to different perceptions concerning the matching results under both sides' evaluation indices. Fourthly, a multi-objective two-sided matching optimization model that aims to maximize the PU of both sides is developed. Finally, an empirical analysis is conducted on three large high-tech electronic-based customers in an industrial park in western Guangdong for demonstrating the effectiveness and rationality of the proposed method.

INDEX TERMS Premium power value-added service, evaluation index, multi-objective optimization, perceived utility, two-sided matching.

NOMENCLATURE

ACRONYMS

PPVS	premium power value-added service
UPS	uninterruptible power supply
DVR	dynamic voltage restorer
SVC	static VAR compensator
NPV	net present value
PSL	premium power value-added service level
IR	investment risk
IE	investment environment
PQS	power quality severity
AAF	average affected frequency
CCD	customer cognition degree
VSS	voltage sag severity
AVSF	average voltage sag frequency
PU	perceived utility
EL	expected level
AL	actual level

SYMBOLS

m	total number of customers
n	total number of products
l	number of customer evaluation indices
t	ordinal number of company indices
i	ordinal number of customers

The associate editor coordinating the review of this manuscript and approving it for publication was Zhigang Liu.

j	ordinal number of products
d	deviation degree
U	comprehensive perceived utility matrix
p	expected level
r	actual level
LG	loss and gain matrix
C	customer set
E	product set
ω	weight
α	disappointment parameter
β	elation parameter

I. INTRODUCTION

The report of the 19th National Congress of the Chinese Communist Party pointed out that the main social contradictions in China have been transformed into the contradiction between people's growing demands for a better life and the unbalanced and inadequate development of the country. With the transformation of the main social contradictions, the development contradiction of Chinese power system has also changed from the lack of power to the insufficient development of power grid and the imbalance of power quality supply and demand. Especially in the era when a large number of new high-tech equipment such as power electronics and microelectronics, are connected to the power grid, customers are eager to obtain better power quality [1], [2]. How to improve the power quality levels while maximizing customers' satisfaction degree is an urgent scientific issue.

The release of No.9 document marks the opening of the electricity retail side [3]. Then, various electricity retail companies spring up. Customers and electricity retail companies have the right to choose products and trading partners freely, and PPVS products have become the common concern [4], [5]. PPVS products refer to the products integrating premium power supply and service that can improve customers' power quality levels. Custom power technologies, such as uninterruptible power supply (UPS), dynamic voltage restorer (DVR), static VAR compensator (SVC), are often used. As an inevitable product under the background of the opening of the electricity retail side, on one hand, PPVS products can improve power quality levels to meet customers' demands. On the other hand, PPVS products can enhance the benefits and image of electricity retail companies. Therefore, it is of great theoretical and practical significance to study the matching problem of customers' PPVS demands and the PPVS levels brought by the products, as well as the decision-making method for PPVS products.

To the authors' best knowledge, existing methods associated with premium power investment decision-making mainly focus on net present value (NPV), payback period, internal rate of return, etc., or the optimal combination of the above methods [6]–[8], which are simple and straightforward. What's more, [9] proposed a premium power decision-making method based on the preference ranking of benefit and NPV. However, all the above methods just took costs and benefits into account, while ignoring the multi-dimensional characteristics when customers evaluate products, and electricity retail companies evaluate customers. Further, a more advanced decision-making model of two-sided matching of customers' PPVS demands and PPVS levels was proposed in [10], but only customers' NPV and electricity retail company's benefit were considered. Actually, since 1962, two-sided matching decision-making problem has been proposed and widely discussed [11]. For example, Z. Zhang *et al.* proposed an approach about stable two-sided matching decision-making with incomplete fuzzy preference relations by considering the disappointment and elation of matching objects [12]. As matching objects usually show different self-confidence levels over different pairwise comparisons, two-sided matching decision-making approach based on fuzzy preference relations with self-confidence was investigated in [13]. In order to consider different linguistic assessments with uncertainty and flexible criteria weight information, a two-sided matching decision-making with multi-granular hesitant fuzzy linguistic term sets and incomplete criteria weight information was developed in [14]. Although two-sided matching decision-making problems have been extensively applied to marriage matching [15], [16], person-job matching [17], [18], knowledge service matching [19], [20], etc., the two-sided matching problem in PPVS product decision-making has not been fully investigated. Considering that the uncertainty usually exists when customers and electricity retail companies make a decision, not only real numbers, but also interval numbers, linguistic variables, and fuzzy sets can be used to characterize the evaluation indices. Thus, considering multiple evaluation indices with different physical attributes, this paper proposes a decision-making model based on two-sided matching of customers' PPVS demands and the PPVS levels brought by the products.

What's more, the PPVS product investment decision-making is actually a comprehensive reflection of both customers' and electricity retail companies' satisfaction degree. The decision-making results may not be accurate when only considering one side's satisfaction degree. Reference [21] shows that multi-objective optimization model can coordinate multiple different scheduling objectives from the perspective of economy, environment and users. In [22], a multi-objective model from the points of economy and environmental benefits is constructed, and different benefit subjects are considered in [23]. Thus, in this paper, a multi-objective optimization model is adopted and constructed by incorporating the maximum satisfaction degree of both customers and electricity retail companies under multiple evaluation indices.

In total, the matching problem of customers' PPVS demands, and the PPVS levels brought by the products depends on both sides' satisfaction degree, which are related to the psychological perceptions of elation or disappointment concerning the potential matching results. In other words, if the AL of a certain evaluation index concerning the matching result is better than the EL, the customer or electricity retail company will experience elation. Conversely, if the AL of a certain evaluation index concerning the matching result is inferior to the EL, a psychological sense of disappointment will be perceived. Therefore, in order to improve the satisfaction degree of customers and electricity retail companies, it is necessary to effectively describe the psychological perception of both sides, and then put forward the corresponding multi-index two-sided matching model.

Based on the above analysis, a decision-making method for PPVS product is proposed in this paper. The basic idea of this method is to first establish a multi-index evaluation system from the perspective of the customers and the electricity retail companies, and then construct a two-sided matching optimization model. Customers' and electricity retail companies' psychological perceptions of elation and disappointment are effectively characterized into the proposed model in this paper. The main contributions of this work are as follows.

- Qualitative and quantitative evaluation indices with different physical attributes are properly formulated and incorporated into an index system from the perspective of both customers and electricity retail companies.
- A two-sided matching of customers' PPVS demands and the PPVS levels brought by the products is fully investigated.
- Comprehensive PU matrix is constructed with the consideration of the deviation degree from the AL to the EL of the evaluation indices, as well as the perceived elation and disappointment of the customers and electricity retail companies, and then an optimization model that aims to maximize both sides' PU is constructed.

The remainder of the paper is organized as follows. Section II describes the two-sided matching problem scenario. Section III constructs the multi-index evaluation system from both customers' and electricity retail companies' point of view. In Section IV, the loss and gain matrices are constructed, with the comparison and deviation degree calculation between the evaluation index's EL and AL. In Section V, based on disappointment theory, customers' and electricity retail companies' PU are fully described. Further, in Section VI, a multi-objective two-sided matching optimization model is constructed, considering the maximization of both sides' PU. Section VII presents an empirical analysis including three large high-tech electronic-based customers in an industrial park in western Guangdong in China. In Section VIII, merits and limitations of the proposed PPVS product decision-making method are discussed. Finally, conclusions are drawn in Section IX.

II. SCENARIO DESCRIPTION

A two-sided matching problem of customers' PPVS demands and the PPVS levels brought by the products with index expectation will be proposed in this paper. Suppose the customer set is $C = \{C_1, C_2, \ldots, C_i, \ldots C_m\}$, where, C_i represents the i-th customer, and $i \in M = \{1, 2, \ldots, m\}$. The set of PPVS products provided by the electricity retail company is $E = \{E_1, E_2, \ldots, E_j, \ldots E_n\}$, where, E_j represents the j-th PPVS product, and $j \in N = \{1, 2, \ldots, n\}$. In order to simplify clarification, this paper only considers one electricity retail company providing various PPVS products. In practice, there may be more than one electricity retail companies, but the decision-making matching method is the same. The index system for customers to evaluate PPVS products is set as $I^C = \{I_1^C, I_2^C, \ldots, I_l^C, \ldots, I_k^C\}$, where, I_l^C is the l-th index that the customer is concerned about, and $l \in K = \{1, 2, \ldots, k\}$. Similarly, the index system for the electricity retail company to evaluate customers is set as $I^E = \left\{I_1^E, I_2^E, \cdots, I_t^E, \cdots, I_g^E\right\}$, where, I_t^E is the t-th index that the company is concerned about, and $t \in G = \{1, 2, \ldots, g\}$. $\omega^C = [\omega_1^C, \omega_2^C, \ldots, \omega_l^C, \ldots, \omega_k^C]$ is the weight vector of I^C, where, ω_l^C is the weight of index I_l^C, and $\sum_{l=1}^{k} \omega_l^C = 1$. $\omega^E = \left[\omega_1^E, \omega_2^E, \cdots, \omega_t^E, \cdots, \omega_g^E\right]$ is the weight vector of I^E, where, ω_t^E is the weight of index I_t^E, and $\sum_{t=1}^{g} \omega_t^E = 1$.

Supposing $P_i^l = \left(p_i^l, h_i^l\right)$ is the expected vector of I_l^C for customer C_i, in which, p_i^l is the EL, and h_i^l is the lowest accepted level. Similarly, $\tilde{P}_j^t = \left(\tilde{p}_j^t, \tilde{h}_j^t\right)$ is the expected vector of I_t^E for E_j, in which, $\tilde{p}_j^t$ is the EL, and $\tilde{h}_j^t$ is the lowest accepted level. $R^C = \left[r_{it}^C\right]_{m\times g}$ is the AL matrix of I^E for customers C, where r_{it}^C is the AL of I_t^E for customer C_i, $i \in M$, $t \in G$. $R^E = \left[r_{jl}^E\right]_{n\times k}$ is the AL matrix of I^C for products E, where r_{jl}^E is the AL of I_l^C for product E_j, $j \in N$, $l \in K$. It should be noted that as the evaluation indices' ELs are based on the survey results of the customers' actual power quality situations, and expectations, the values of the evaluation indices' ELs are set by the customers and the electricity retail company. That is, the ELs and ALs of the evaluation indices are customer-specific, and company-specific, which can be obtained through actual survey.

Considering the differences of the evaluation indices' physical attributes, real numbers, interval numbers, linguistic variables and intuitionistic fuzzy numbers are utilized in this paper. In fact, the indices can also be expressed in other ways, but the PPVS products decision-making method is the same.

It is assumed that I^{C1}, I^{C2}, I^{C3}, and I^{C4} are the subsets of I^C, representing the real numbers subset, interval numbers subset, linguistic variables subset, and intuitionistic fuzzy numbers subset, respectively. The above subsets are expressed as follows.

$$
\begin{aligned}
I^{C1} &= \left\{I_1^C, I_2^C, \cdots, I_{k_1}^C\right\}, \quad K_1 = \{1, 2, \cdots, k_1\} \\
I^{C2} &= \left\{I_{k_1+1}^C, I_{k_1+2}^C, \cdots, I_{k_2}^C\right\}, \\
K_2 &= \left\{k_1+1, k_1+2, \cdots, k_2\right\} \\
I^{C3} &= \left\{I_{k_2+1}^C, I_{k_2+2}^C, \cdots, I_{k_3}^C\right\}, \\
K_3 &= \left\{k_2+1, k_2+2, \cdots, k_3\right\} \\
I^{C4} &= \left\{I_{k_3+1}^C, I_{k_3+2}^C, \cdots, I_{k_4}^C\right\}, \\
K_4 &= \left\{k_3+1, k_3+2, \cdots, k_4\right\}
\end{aligned}
$$

I^{C1}, I^{C2}, I^{C3}, and I^{C4} satisfy $I^{C1} \cup I^{C2} \cup I^{C3} \cup I^{C4} = I^{C} = I^{cost} \cup I^{benefit}$, where, I^{cost} represents the cost-type index subset of I^{C}, and $I^{benefit}$ is the benefit-type index subset of I^{C}.

Similarly, I^{E1}, I^{E2}, I^{E3}, and I^{E4} are the subsets of I^{E}, representing the real numbers subset, interval numbers subset, linguistic variables subset, and intuitionistic fuzzy numbers subset, respectively. The above subsets are expressed as follows.

$$\begin{aligned} I^{E1} &= \left\{I_1^E, I_2^E, \cdots, I_{g_1}^E\right\}, \quad G_1 = \{1, 2, \cdots, g_1\} \\ I^{E2} &= \left\{I_{g_1+1}^E, I_{g_1+2}^E, \cdots, I_{g_2}^E\right\}, \\ G_2 &= \{g_1+1, g_1+2, \cdots, g_2\} \\ I^{E3} &= \left\{I_{g_2+1}^E, I_{g_2+2}^E, \cdots, I_{g_3}^E\right\}, \\ G_3 &= \{g_2+1, g_2+2, \cdots, g_3\} \\ I^{E4} &= \left\{I_{g_3+1}^E, I_{g_3+2}^E, \cdots, I_{g_4}^E\right\}, \\ G_4 &= \{g_3+1, g_3+2, \cdots, g_4\} \end{aligned}$$

I^{E1}, I^{E2}, I^{E3}, and I^{E4} satisfy $I^{E1} \cup I^{E2} \cup I^{E3} \cup I^{E4} = I^{E} = I^{Ecost} \cup I^{Ebenefit}$, where, I^{Ecost} represents the cost-type index subset of I^{E}, and $I^{Ebenefit}$ is the benefit-type index subset of I^{E}.

Based on the customers' and electricity retail company's evaluation indices' expected vector P_i^l and $\tilde{P}_j^t$, AL matrix R^C and R^E, weight vector ω^C and ω^E, aiming at the two-sided matching problem of the customers' PPVS demands and the PPVS levels brought by the products, both sides' PU concerning potential matching results are characterized. Then, the final matching results can be obtained by reasonable and effective decision-making analysis method.

III. MULTI-INDEX SYSTEM CONSTRUCTION

At first, from the perspective of customers, the index system for evaluating PPVS products is constructed, including NPV, premium power value-added service level (PSL), investment risk (IR), and investment environment (IE). Then, from the perspective of electricity retail company, the index system for evaluating customers is constructed, including power quality severity (PQS), benefit, average affected frequency (AAF), and customer cognition degree (CCD). Based on each index's attribute, the indices are expressed by real numbers, interval numbers, linguistic variables and intuitionistic fuzzy numbers, respectively.

A. CUSTOMER EVALUATION INDEX SYSTEM

(1) net present value (NPV)

When customers make an investment in the PPVS products, NPV refers to the difference between the present value of future cash inflow and the initial investment cost [6], which can be calculated by (1). Larger NPV implies greater benefits of investing in the PPVS products, and the customers are more willing to make an investment.

$$NPV = \sum_{t=0}^{T} \frac{I_t}{(1+p_1)^t} - Z \tag{1}$$

where, T is the life cycle of the PPVS products. I_t is the net cash inflow for the t-th year. p_1 is the discount rate, and Z is the initial investment cost, including product purchase cost, installation cost, service cost, and so on.

(2) premium power value-added service level (PSL)

The improvement degree of power quality depends on the PSL brought by the PPVS products. PSL is divided into three levels, expressed by (2). The higher the PSL is, the greater the improvement degree of power quality is. Then, customers would like to make more investment in the PPVS products.

$$PSL = \{A|AA|AAA\} \tag{2}$$

where, A is for normal level, the term AA is for medium level, and AAA is for premium level.

(3) investment risk (IR)

IR refers to the possibility that customers may suffer profit loss or even capital loss due to policy changes, management errors or any other reasons when customers invest in the PPVS products. Smaller IR indicates greater profits brought to the customers. In this case, the customers' willingness to pay are stronger. In general, IR is uncertain, but an upper and lower limit value of IR is easy to be obtained. That is, IR can be expressed by an interval number. Based on [24], [25], IR can be represented by

$$IR = \left[IR_{\text{low}},\ IR_{\text{high}}\right] \tag{3}$$

where IR_{low} and IR_{high} are the lower limit value and the upper limit value, respectively.

(4) investment environment (IE)

IE refers to various surrounding conditions accompanying the whole products investment process, including natural, social, economical, political, legal elements, etc. With the improvement of the IE, the PPVS products are more worthy of customers' investment, and more benefits will be brought to the customers. IE cannot be fully controlled by the customers, and most of the time, only the good or bad degree that the IE belongs to is known. Therefore, intuitionistic fuzzy sets proposed by Atanassov in Bulgarian [26] are introduced to characterize IE, which is shown in (4).

$$IE = \langle \mu,\ v \rangle \tag{4}$$

where, μ is the membership degree, representing the good degree that IE is subordinate to, while v is the non-membership degree, representing the bad degree that IE is subordinate to. λ is the hesitation degree, i.e., $\lambda = 1 - \mu - v$, representing the degree that IE belongs to good or bad is uncertain.

B. ELECTRICITY RETAIL COMPANY EVALUATION INDEX SYSTEM

(1) power quality severity (PQS)

PQS is an important index for electricity retail company to evaluate the power quality's impact on customers. The more serious the power quality is, the greater the economic loss customers will tolerate. Then, customers' willingness to invest in PPVS products will be strong. This paper focuses on the customers who are seriously affected by voltage sags. Voltage sag severity (VSS) defined in IEEE Std.1564 [27] is introduced as an evaluation index, which is shown in (5). In practice, different types of customers may undergo different kinds of power quality disturbances. Besides VSS, PQS can be other severity indices, which do not affect the proposed decision-making method.

$$VSS = \frac{1 - V_{\text{sag}}}{1 - V_{\text{std}}(T)} \tag{5}$$

where, V_{sag} and T are voltage sag magnitude and duration respectively. $V_{\text{std}}(T)$ represents the voltage sag magnitude on the SEMI F47 curve or the equipment's true immunity curve when the voltage sag duration is equal to T.

In general, equipment's voltage sag tolerance levels show obvious interval characteristics [28], [29]. For example, the typical uncertain regions of personal computer's voltage sag magnitude and duration are [0.3, 0.9] p.u. and [20], [400] ms. Thus, an interval number can be used to represent VSS.

(2) electricity retail company's benefit (Benefit)

The electricity retail company will obtain benefit when providing PPVS products to customers, which is expressed by (6). The greater the benefits brought to the company are, the greater the preference of the company for the corresponding customers is, and the stronger the willingness to corporate with the customers is.

$$I_{\text{in}} = Z + \sum_{t=0}^{T} \frac{I_{\text{out}}}{(1+p_2)^t} \tag{6}$$

where, I_{in} refers to benefit. Z is the contract fee paid by the customers. I_{out} is the annual operation and maintenance cost paid by the customers, and p_2 is the annual discount rate, which is determined by the expected profit of the electricity retail company.

(3) average affected frequency (AAF)

AAF means the average affected number of power quality disturbance events that bring economic losses to the customers. As this paper focuses on the customers who are mostly affected by voltage sags, average voltage sag frequency (AVSF) is used to characterize the number of affected voltage sags, which is an important factor affecting customers' economic losses. AVSF can be determined by the data recorded by the voltage sag monitor device installed at the customer bus interface, and the voltage sag immunity of the customers' equipment. The smaller the AVSF is, the greater the utility brought by investing in the products is, the greater the profit brought to the electricity retail company will be, and the stronger the company's willingness to cooperate is.

As equipment's voltage sag immunity shows obvious interval characteristics, AVSF can be expressed by an interval number, as follows.

$$AVSF = \left[AVSF_{\text{low}},\ AVSF_{\text{high}}\right] \tag{7}$$

where, $AVSF_{\text{low}}$ is the lower limit value, and $AVSF_{\text{high}}$ is the higher limit value.

(4) customer cognition degree (CCD)

CCD refers to the customers' understanding of voltage sags and PPVS products, which are divided into five levels, as shown in (8). With the improvement of CCD, the customers will perceive more utility brought by the products. Then, it is easier for the company to reach an agreement with the customers.

$$CCD = \{VL|L|M|H|VH\} \tag{8}$$

where, VL, L, M, H, and VH represent that the CCD is very low, low, medium, high, and very high, respectively.

IV. LOSS AND GAIN MATRIX CONSTRUCTION

There exists difference between the EL and AL of evaluation indices for both customers and electricity retail company. For benefit-type index, if the EL is lower than the AL, customers and electricity retail company perceive gains. Otherwise, losses are perceived. For cost-type index, if the EL is greater than the AL, customers and electricity retail company perceive gains. Otherwise, losses are perceived. Take customers as an example. At first, the EL and AL of the evaluation index is compared. Then, the deviation degree from the AL to the EL is calculated. Finally, the loss and gain matrices are constructed.

A. COMPARISON BETWEEN EL AND AL

The comparison between EL and AL depends on the physical attributes of the evaluation indices, which are discussed as follows.

(1) The evaluation index is a real number.

The evaluation index's EL p_i^l and AL r_{jl}^E are real numbers, i.e., $I_l^C \in I^{C1}$. The comparison is easy to do.

(2) The evaluation index is an interval number.

The evaluation index's EL $p_i^l = \left[p_i^{l\,low}, p_i^{l\,up}\right]$ and AL $r_{jl}^E = \left[r_{jl}^{E\,low}, r_{jl}^{E\,up}\right]$ are interval numbers, i.e., $I_l^C \in I^{C2}$. The comparison method is as follows.

Calculate four intermediate values based on (9) and (10).

$$\left(p_i^l\right)' = \left(p_i^{l\,low} + p_i^{l\,up}\right)/2,\ \ \left(r_{jl}^E\right)' = \left(r_{jl}^{E\,low} + r_{jl}^{E\,up}\right)/2 \tag{9}$$

$$\left(p_i^l\right)'' = p_i^{l\,up} - p_i^{l\,low},\ \ \left(r_{jl}^E\right)'' = r_{jl}^{E\,up} - r_{jl}^{E\,low} \tag{10}$$

$\left(p_i^l\right)' >$ (or $<$) $\left(r_{jl}^E\right)'$ gives $p_i^l >$ (or $<$) r_{jl}^E, and if $\left(p_i^l\right)' = \left(r_{jl}^E\right)'$, $\left(p_i^l\right)'' >$ (or $<$) $\left(r_{jl}^E\right)''$ gives $p_i^l <$ (or $>$) r_{jl}^E.

(3) The evaluation index is a linguistic variable.

The evaluation index's EL p_i^l and AL r_{jl}^E are linguistic variables, i.e., $I_l^C \in I^{C3}$. $p_i^l \succ$ (or $\prec$) r_{jl}^E gives $p_i^l >$ (or $<$) r_{jl}^E, where $\succ$ and $\prec$ means superior to and inferior to.

(4) The evaluation index is an intuitionistic fuzzy number.

The evaluation index's EL $p_i^l = \left\langle p_i^{l\mu}, p_i^{lv} \right\rangle$ and AL $r_{jl}^E = \left\langle r_{jl}^{E\mu}, r_{jl}^{Ev} \right\rangle$ are intuitionistic fuzzy numbers, i.e., $I_l^C \in I^{C4}$. The comparison result depends on the difference between membership degree and non-membership degree, i.e., $p_i^{l\mu} - p_i^{lv} >$ (or $<$) $r_{jl}^{E\mu} - r_{jl}^{Ev}$ gives $p_i^l >$ (or $<$) r_{jl}^E.

B. CALCULATION OF DEVIATION DEGREE FROM THE AL TO THE EL

Deviation degree from the AL to the EL can be characterized by the distance between the AL and the EL. The larger the distance is, the greater the deviation degree is, and the stronger the perceptions of customers and electricity retail company are. In this paper, Euler distance is used to characterize the deviation degree, which is denoted as d_{ij}^l.

(1) When $I_l^C \in I^{C1}$, d_{ij}^l is calculated by (11).

$$d_{ij}^l = \left| p_i^l - r_{jl}^E \right| \tag{11}$$

(2) When $I_l^C \in I^{C2}$, d_{ij}^l is calculated by (12).

$$d_{ij}^l = \sqrt{\frac{1}{2}\left[\left(p_i^{l\,low} - r_{jl}^{E\,low}\right)^2 + \left(p_i^{l\,up} - r_{jl}^{E\,up}\right)^2\right]} \tag{12}$$

(3) When $I_l^C \in I^{C3}$, the linguistic variables are converted to interval numbers, as shown in (13). Then, the deviation degree d_{ij}^l is calculated by (12).

$$p_i^l = \left(p_i^{l\,low}, p_i^{l\,up}\right) = \left(\max\left\{\frac{y-1}{y_1}, 0\right\}, \min\left\{\frac{y+1}{y_1}, 1\right\}\right) \tag{13}$$

where, $y = \{0, 1, 2, \cdots, y_1\}$.

(4) When $I_l^C \in I^{C4}$, d_{ij}^l is calculated by (14).

$$d_{ij}^l = \sqrt{\frac{1}{3}\left[\left(p_i^{l\mu} - r_{jl}^{E\mu}\right)^2 + \left(p_i^{lv} - r_{jl}^{Ev}\right)^2 + \left(p_i^{l\lambda} - r_{jl}^{E\lambda}\right)^2\right]} \tag{14}$$

where, $p_i^{l\lambda}$ and $r_{jl}^{E\lambda}$ are the hesitation degree of the evaluation index's EL p_i^l and AL r_{jl}^E, i.e., $p_i^{l\lambda} = 1 - p_i^{l\mu} - p_i^{lv}$ and $r_{jl}^{E\lambda} = 1 - r_{jl}^{E\mu} - r_{jl}^{Ev}$.

C. LOSS AND GAIN MATRIX CONSTRUCTION

Based on the comparison results and deviation degree calculation results, the loss and gain matrix $(\mathrm{LG})^l = \left[lg_{ij}^l\right]_{m\times n}$ for index I_l^C can be constructed, in which, lg_{ij}^l is customer C_i's loss and gain value for product E_j. Based on the cost attribute and benefit attribute of the evaluation index I_l^C, the detailed determination methods of lg_{ij}^l are as follows.

(1) If I_l^C is cost-type index, i.e., $I_l^C \in I^{cost}$, lg_{ij}^l is determined as follows.

If $r_{jl}^E < p_i^l$, customer C_i will perceive gain, i.e.,

$$lg_{ij}^l = d_{ij}^l \tag{15}$$

If $r_{jl}^E > p_i^l$, customer C_i will perceive loss, i.e.,

$$lg_{ij}^l = -d_{ij}^l \tag{16}$$

(2) If I_l^C is benefit-type index, i.e., $I_l^C \in I^{benefit}$, lg_{ij}^l is determined as follows.

If $r_{jl}^E < p_i^l$, customer C_i will perceive loss, i.e.,

$$lg_{ij}^l = -d_{ij}^l \tag{17}$$

If $r_{jl}^E > p_i^l$, customer C_i will perceive gain, i.e.,

$$lg_{ij}^l = d_{ij}^l \tag{18}$$

Similarly, the loss and gain matrix $\widetilde{(\mathrm{LG})}^t = \left[\widetilde{lg}_{ij}^t\right]_{m\times n}$ for index I_t^E can be constructed, in which, $\widetilde{lg}_{ij}^t$ is the electricity retail company's loss and gain value regarding product E_j when evaluating customer C_i.

It should be noted that if the index I_l^C's AL r_{jl}^E for product E_j does not reach the lowest accepted level h_i^l of customer C_i, C_i will not match with E_j. To simplify, the loss and gain value lg_{ij}^l is denoted as $-$M. Similarly, if the index I_t^E's AL r_{it}^C for customer C_i does not reach the lowest accepted level $\tilde{h}_j^t$ of product E_j, E_j will not match with C_i, and the loss and gain value $\widetilde{lg}_{ij}^t$ is denoted as $-$M.

In order to eliminate the dimension's influence on the results, the loss and gain matrices $(\mathrm{LG})^l = \left[lg_{ij}^l\right]_{m\times n}$ and $\widetilde{(\mathrm{LG})}^t = \left[\widetilde{lg}_{ij}^t\right]_{m\times n}$ for customers and electricity retail company are normalized to $\left(\overline{\mathrm{LG}}\right)^l = \left[\overline{lg}_{ij}^l\right]_{m\times n}$ and $\left(\overline{\widetilde{\mathrm{LG}}}\right)^t = \left[\overline{\widetilde{lg}}_{ij}^t\right]_{m\times n}$. Take $\overline{lg}_{ij}^l$ as an example, its formulation is shown in (19), which is the same for $\overline{\widetilde{lg}}_{ij}^t$.

$$\overline{lg}_{ij}^l = lg_{ij}^l / \left(\max\left|lg_{ij}^l\right|\right) \quad I_l^C \in I^C \tag{19}$$

V. PERCEIVED UTILITY MATRIX CONSTRUCTION

Utility is a comprehensive measure of the benefits and satisfaction degree brought by the matching results of customers' PPVS demands and PPVS levels, which is related to the psychological perceptions of both sides. On one hand, if customers' loss and gain value concerning the PPVS products is larger than zero, or the company's loss and gain value concerning the customers is larger than zero, both sides are pleased with the matching results concerning the corresponding evaluation index. On the other hand, if the loss and gain value is smaller than zero, both customers and company are disappointed with the matching results concerning the corresponding evaluation index. Obviously, customers' and company's perceived elation or disappointment is related to the satisfaction degree concerning the matching results. In order to better describe the satisfaction degree of customers and electricity retail company, based on the theory of disappointment, the elation function $H(\cdot)$ and the disappointment function $D(\cdot)$ [30] are introduced, as shown in (20) and (21).

Then, the elation value and disappointment value of both sides under the evaluation index can be calculated.

$$H(x) = 1 - \beta^{x} \tag{20}$$

$$D(x) = \alpha^{-x} - 1 \tag{21}$$

where, x is the loss and gain value. β $(0 < \beta < 1)$ is the elation parameter. As for the same gain, the larger the β is, the less elation the customers or the company will perceive. α $(0 < \alpha < 1)$ is the disappointment parameter. As for the same loss, the larger the α is, the less disappointment the customers or the company will perceive. References [30]–[33] showed that for a majority of the investment decision-making processes, $\alpha = \beta = 0.8$, thus, in this paper, α and β are set as 0.8. In practice, α and β can also be set as other values based on customers' and electricity retail company's preferences and aversion degree towards loss and gain.

Based on the constructed elation function $H(\cdot)$ and disappointment function $D(\cdot)$, combined with the normalized loss and gain matrices, i.e., $\left(\overline{\mathrm{LG}}\right)^{l} = \left[\overline{lg}_{ij}^{l}\right]_{m\times n}$ and $\left(\widetilde{\overline{\mathrm{LG}}}\right)^{t} = \left[\widetilde{\overline{lg}}_{ij}^{t}\right]_{m\times n}$, customers' PU matrices $U^{l} = \left[u_{ij}^{l}\right]_{m\times n}$ concerning index I_l^C, and electricity retail company's PU matrices $\widetilde{U}^{t} = \left[(\widetilde{u})_{ij}^{t}\right]_{m\times n}$ concerning index I_t^E can be constructed. The determination method of u_{ij}^{l} and $(\widetilde{u})_{ij}^{t}$ are shown in (22) and (23).

$$u_{ij}^{l} = \begin{cases} H\left(\overline{lg}_{ij}^{l}\right), & \overline{lg}_{ij}^{l} > 0 \\ 0, & \overline{lg}_{ij}^{l} = 0 \quad i \in M, j \in N, l \in K \\ D\left(\overline{lg}_{ij}^{l}\right), & \overline{lg}_{ij}^{l} < 0 \end{cases} \tag{22}$$

$$(\widetilde{u})_{ij}^{t} = \begin{cases} H\left(\widetilde{\overline{lg}}_{ij}^{t}\right), & \widetilde{\overline{lg}}_{ij}^{t} > 0 \\ 0, & \widetilde{\overline{lg}}_{ij}^{t} = 0 \quad i \in M, j \in N, t \in G \\ D\left(\widetilde{\overline{lg}}_{ij}^{t}\right), & \widetilde{\overline{lg}}_{ij}^{t} < 0 \end{cases} \tag{23}$$

Further, taking a full consideration of each evaluation index's influence, customers' and electricity retail company's comprehensive PU matrices, i.e., $U = \left[u_{ij}\right]_{m\times n}$ and $\widetilde{U} = \left[\widetilde{u}_{ij}\right]_{m\times n}$, can be constructed. The formulation of u_{ij} and $\widetilde{u}_{ij}$ are shown in (24) and (25).

$$u_{ij} = \sum_{l=1}^{k} \omega_l^C u_{ij}^{l}, \quad i \in M,\ j \in N,\ l \in K \tag{24}$$

$$\widetilde{u}_{ij} = \sum_{t=1}^{g} \omega_t^E \widetilde{u}_{ij}^{t}, \quad i \in M,\ j \in N,\ t \in G \tag{25}$$

VI. TWO-SIDED MATCHING OPTIMIZATION MODEL CONSTRUCTION AND SOLVING

The matching degree between customers' PPVS demands and the PPVS levels brought by the products is closely related to both sides' satisfaction degree. The higher the PU is, the greater the satisfaction degree is, and the greater the probability of success matching is.

In this section, based on customers' and electricity retail company's comprehensive PU matrices, a multi-objective two-sided matching optimization model is constructed. The solving method is also analyzed.

A. TWO-SIDED MATCHING OPTIMIZATION MODEL CONSTRUCTION

Based on the constructed comprehensive PU matrices, i.e., U and $\widetilde{U}$ in Section V, a multi-objective two-sided matching optimization model is established. In the model, the lowest accepted levels of evaluation indices are as the constraint conditions and the maximization of both sides' comprehensive PU are as the objectives. Without losing generality, it is assumed that each customer C_i matches with at most one PPVS product E_j, and each PPVS product matches with at most one customer. The 0-1 variable x_{ij} is introduced, i.e., $x_{ij} = 0$ means C_i does not match with E_j, and $x_{ij} = 1$ means C_i matches with E_j. The constructed multi-objective two-sided matching optimization model is shown in (26).

$$\max U_1 = \sum_{i=1}^{m} \sum_{j=1}^{n} u_{ij} x_{ij} \tag{26a}$$

$$\max U_2 = \sum_{i=1}^{m} \sum_{j=1}^{n} \widetilde{u}_{ij} x_{ij} \tag{26b}$$

$$s.t. \quad \sum_{i=1}^{m} x_{ij} \le 1, \quad j \in N \tag{26c}$$

$$\sum_{j=1}^{n} x_{ij} \le 1, \quad i \in M \tag{26d}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \left(u_{ij} + \widetilde{u}_{ij}\right) x_{ij} \ge -mn \tag{26e}$$

$$x_{ij} = 0 \ \text{ or } \ 1, \quad i \in M,\ j \in N \tag{26f}$$

In the proposed model, equations (26a) and (26b) are objective functions, indicating that the comprehensive PU of customers and electricity retail company should be maximized as much as possible. Equations (26c) $\sim$ (26e) are constraint conditions. Equations (26c) and (26d) are two-sided matching constraint conditions. Equations (26c) indicates that each PPVS product matches with at most one customer, while equations (26d) indicates that each customer matches with at most one PPVS product. Equations (26e) is the lowest accepted level constraint for the customers and the company, ensuring that both sides can reach the lowest accepted levels.

B. TWO-SIDED MATCHING OPTIMIZATION MODEL SOLVING

In this paper, the linear weighting method [34] is used to transform the multi-objective two-sided matching optimization model into a single-objective optimization model. Suppose that ω_1 and ω_2 are the weights of the objective functions U_1 and U_2, satisfying $0 \le \omega_1, \omega_2 \le 1$, and $\omega_1 + \omega_2 = 1$. Thus, a single-objective optimization model can be represented by

$$\max \bar{U} = \omega_1 \sum_{i=1}^{m}\sum_{j=1}^{n} u_{ij}x_{ij} + \omega_2 \sum_{i=1}^{m}\sum_{j=1}^{n} \widetilde{u}_{ij}x_{ij} \quad (27a)$$

$$s.t. \quad \sum_{i=1}^{m} x_{ij} \le 1, \quad j \in N \quad (27b)$$

$$\sum_{j=1}^{n} x_{ij} \le 1, \quad i \in M \quad (27c)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} \left(u_{ij} + \widetilde{u}_{ij}\right) x_{ij} \ge -mn \quad (27d)$$

$$x_{ij} = 0 \text{ or } 1, \quad i \in M, \quad j \in N \quad (27e)$$

In order to reflect the fairness between customers and electricity retail company, let $\omega_1 = \omega_2 = 0.5$. MATLAB is used to solve the single-objective optimization model.

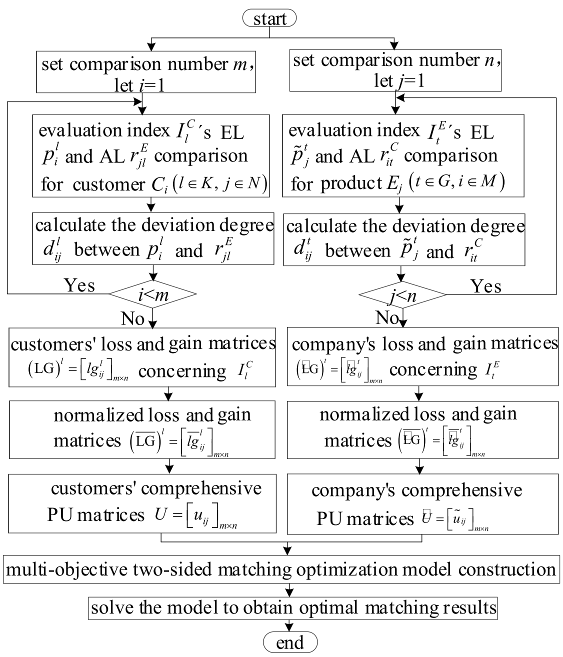

FIGURE 1. Flowchart of multi-objective two-sided matching decision-making considering multiple indices.

C. FLOWCHART OF THE PROPOSED METHOD

Based on the above analysis, considering customers' and electricity retail company's perceived elation and disappointment, the proposed multi-objective two-sided matching decision-making process is shown in Fig. 1.

Generally speaking, the proposed method can be divided into two steps. The first step is the multi-objective two-sided matching optimization model construction, including EL and AL comparison, deviation degree calculation, loss and gain matrices establishment, normalization, and comprehensive PU matrices construction. The second step is to solve the model to obtain the optimal matching results. Accordingly, the computational complexity of the multi-objective two-sided matching decision-making considering multiple indices can be analyzed as follows.

EL and AL comparison: It is assumed that the total number of customers is m. The number of products proposed by the electricity retail company is n. The evaluation index number for each customer is k, and that for company is g. The cost of EL and AL comparison is $O(mk) + O(ng)$.

Deviation degree calculation: The computational complexity of the deviation degree calculation is the same as that of the EL and AL comparison, i.e., $O(mk) + O(ng)$.

Loss and gain matrices establishment: The loss and gain matrices establishment are actually the combination of the results of EL and AL comparison, and deviation degree calculation. The computational cost of loss and gain matrices establishment is $O(mnk) + O(mng)$.

Normalization: The cost of normalization is the same as that of the loss and gain matrices establishment, i.e., $O(mnk) + O(mng)$.

Comprehensive PU matrices construction: The comprehensive PU matrices construction contains two steps. First, PU concerning each evaluation index considering elation and disappointment psychological perceptions are calculated. Then, considering each evaluation index's weight, the comprehensive PU matrices can be constructed. For the first step, the computational cost is $O(mnk) + O(mng)$. And for the second step, the computational cost is $2O(mnk) + 2O(mng)$. Thus, the total computational complexity of comprehensive PU matrices construction is $O(mnk) + O(mng) + 2O(mnk) + 2O(mng) = O(mnk) + O(mng)$.

Multi-objective two-sided matching optimization model construction: Based on the above analysis, the computational complexity of multi-objective two-sided matching optimization model construction can be obtained, i.e., $[O(mk) + O(ng)] + [O(mk) + O(ng)] + [O(mnk) + O(mng)] + [O(mnk) + O(mng)] + [O(mnk) + O(mng)] = O(mnk) + O(mng)$.

Model solving: In this paper, the multi-objective two-sided matching optimization model solving is performed by *linprog* function in MATLAB. For a *linprog* calculation with W_1 parameters, and W_2 iterations, its complexity is $O(W_1W_2)$. As the number of customers is m, and the number of products is n, the cost of multi-objective two-sided matching optimization model solving is $O(mnW_2)$.

Therefore, the total computational complexity of the proposed method is $O(mnk) + O(mng) + O(mnW_2) = O(mnW)$, where, W equals to $k + g + W_2$, depending on the number of the customers' and electricity retail company's evaluation indices, as well as the number of iterations.

VII. EMPIRICAL ANALYSIS

A. EMPIRICAL BACKGROUND, DATA,AND HYPOTHESIS

Three large high-tech electronic-based customers $C = \{C_1, C_2, C_3\}$ located in an industrial park in western Guangdong

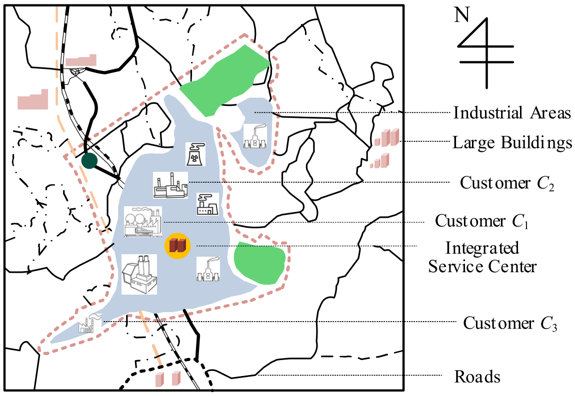

FIGURE 2. Geographical locations of customers in the industrial park.

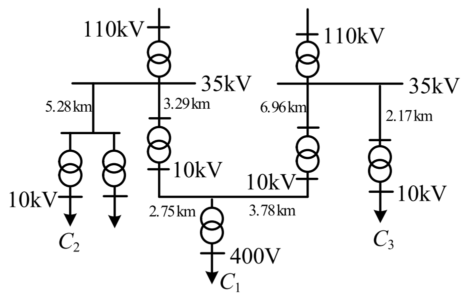

FIGURE 3. Distribution network diagram of the industrial park.

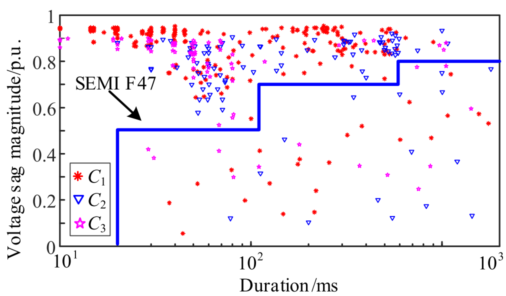

FIGURE 4. Voltage sag distributions at bus interface for customers $C_1 \sim C_3$ from 2013 to 2019.

in China are investigated and analyzed. The customers' geographical locations are shown in Fig. 2. There are two 110kV substations in the park, and the distribution network diagram is plotted in Fig. 3.

Customers in the industrial park are very sensitive to voltage sags. Voltage sag monitoring devices are installed at the bus interface of customers $C_1 \sim C_3$, and the recorded voltage sag distributions from 2013 to 2019 are shown in Fig. 4. The total voltage sag frequency and the number of voltage sags leading to economic losses suffered by customers $C_1 \sim C_3$ are plotted in Fig. 5.

According to the voltage sags' influence on the customers in the park [35], [36], the PPVS products provided by the electricity retail company are $E = \{E_1, E_2, E_3, E_4\}$, as shown

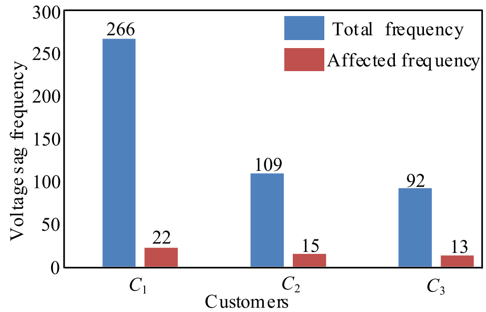

FIGURE 5. The total frequency and the affected number of voltage sags suffered by customers $C_1 \sim C_3$ from 2013 to 2019.

TABLE 1. PPVS products provided by the electricity retail company.

Product	Custom Power Technology	Purchase and Installation Cost ($\times 10^4$¥)
E_1	SVC	16.9547
E_2	DVR	31.9254
E_3	Static UPS, 350kVA, 90min	82.0892
E_4	Static UPS, 350kVA, 90min	126.5113

in TABLE 1. In order to prove the proposed method in principle and simplify the calculation, it is further assumed that each product contains only one custom power technology. In practice, it is likely to be an optimal combination of multiple custom power technologies, but the above assumption does not affect the operation of the proposed two-sided matching optimization method.

Based on the survey results of the actual voltage sag situations from 2013 to 2019, the index I_l^C's expected vector $P_i^l = (p_i^l, h_i^l)$ $(i = 1, 2, 3.\ l = 1, 2, 3, 4)$ for the customers when evaluating PPVS products are shown in TABLE 2. The AL r_{jl}^E $(j = 1, 2, 3, 4.\ l = 1, 2, 3, 4)$ of I_l^C $(l = 1, 2, 3, 4)$ for company's products are shown in TABLE 3. Similarly, the index I_t^E's expected vector $\tilde{P}_j^t = (\tilde{p}_j^t, \tilde{h}_j^t)$ $(j = 1, 2, 3, 4.\ t = 1, 2, 3, 4)$ for the electricity retail company when evaluating customers is shown in TABLE 4. The evaluation index I_t^E's AL r_{it}^C $(i = 1, 2, 3.\ t = 1, 2, 3, 4)$ for the customers are shown in TABLE 5.

It should be noted that although only three large electronic-based industrial customers are investigated and analyzed, the proposed approach can be scalable in the aspects of the customer number, the industrial park size, the electricity retail company's number, and the evaluation index's number, type and attribute.

B. CUSTOMERS' AND ELECTRICITY RETAIL COMPANY'S LOSS AND GAIN MATRICES CONSTRUCTION

Based on (9) $\sim$ (19), customers' normalized loss and gain matrices $\left(\overline{\text{LG}}\right)^l = \left[\overline{lg}_{ij}^l\right]_{m\times n}$ concerning evaluation indices I_l^C $(l = 1, 2, 3, 4)$ are as follows.

$$\left(\overline{\text{LG}}\right)^1 = \left[\overline{lg}_{ij}^1\right]_{3\times 4} = \begin{bmatrix} -0.2364 & 0.5155 & 0.6313 & -0.4039 \\ -0.5758 & 0.1761 & 0.2919 & -0.7433 \\ 0.1323 & 0.8842 & 1.0000 & -0.0352 \end{bmatrix}$$

TABLE 2. Expected vector $P_i^l = \left(p_i^l, h_i^l\right)$ $(i = 1, 2, 3.\ l = 1, 2, 3, 4)$ of index I_l^C.

Customer	NPV/×10⁶ ¥	PSL	IR	IE
C_1	(115.0625, 22.9247)	(AAA, A)	([0.2347, 0.5014], [0.3297, 0.5142])	(<0.5786, 0.2047>, <0.5139, 0.2871>)
C_2	(140.5344, 29.0731)	(AAA, AA)	([0.1579, 0.4973], [0.2683, 0.5022])	(<0.6932, 0.1872>, <0.5977, 0.2111>)
C_3	(87.39483, 14.6683)	(AA, A)	([0.3031, 0.6278], [0.3574, 0.6521])	(<0.5035, 0.2115>, <0.4213, 0.1030>)

TABLE 3. Actual level r_{jl}^E $(j = 1, 2, 3, 4.\ l = 1, 2, 3, 4)$ of index I_l^C for products.

Product	NPV/×10⁶ ¥	PSL	IR	IE
E_1	97.3216	AA	[0.2090, 0.5499]	<0.5211, 0.1074>
E_2	153.7491	AAA	[0.1938, 0.3834]	<0.6575, 0.1750>
E_3	162.4369	AAA	[0.1640, 0.4654]	<0.6837, 0.1243>
E_4	84.7523	AA	[0.2875, 0.4631]	<0.5024, 0.1291>

TABLE 4. Expected vector $\tilde{P}_j^t = \left(\tilde{p}_j^t, \tilde{h}_j^t\right)$ $(j = 1, 2, 3, 4.\ t = 1, 2, 3, 4)$ of index I_t^E.

Product	VSS	Benefit/×10⁶ ¥	AVSF	CCD
E_1	([2.5794, 4.1859], [6.0000, 8.0000])	(83.2468, 62.5318)	([10, 25], [13, 30])	(H, M)
E_2	([3.3456, 8.7233], [6.0000, 10.0000])	(149.1522, 96.7234)	([20, 37], [25, 40])	(VH, M)
E_3	([3.7953, 8.9724], [6.0000, 10.0000])	(160.9753, 93.2312)	([23, 47], [25, 50])	(VH, M)
E_4	([1.8775, 3.9236], [6.0000, 8.0000])	(76.5218, 57.1113)	([10, 27], [17, 30])	(H, M)

TABLE 5. Actual level r_{it}^C $(i = 1, 2, 3.\ t = 1, 2, 3, 4)$ of index I_t^E for customers.

Customer	VSS	Benefit/×10⁶ ¥	AVSF	CCD
C_1	[3.1527, 4.8105]	122.1186	[16, 27]	H
C_2	[3.6973, 7.6290]	165.2351	[18, 30]	VH
C_3	[1.4275, 3.7967]	102.8796	[7, 20]	H

$$\left(\overline{\mathrm{LG}}\right)^2 = \left[\overline{lg}_{ij}^2\right]_{3\times 4} = \begin{bmatrix} -1 & 0 & 0 & -1 \\ -1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

$$\left(\overline{\mathrm{LG}}\right)^3 = \left[\overline{lg}_{ij}^3\right]_{3\times 4} = \begin{bmatrix} -0.2050 & 0.4665 & 0.2963 & -0.2436 \\ -0.2739 & 0.4461 & 0.1213 & -0.5006 \\ 0.4563 & 1.0000 & 0.7987 & 0.6179 \end{bmatrix}$$

$$\left(\overline{\mathrm{LG}}\right)^4 = \left[\overline{lg}_{ij}^4\right]_{3\times 4} = \begin{bmatrix} 0.3587 & 0.4116 & 0.6821 & -0.3213 \\ -0.6316 & -0.1331 & 0.2486 & -0.7172 \\ 0.4823 & 0.7414 & 1.0000 & 0.3466 \end{bmatrix}$$

In the same way, the electricity retail company's normalized loss and gain matrices $\left(\widetilde{\overline{\mathrm{LG}}}\right)^t = \left[\widetilde{\overline{lg}}_{ij}^t\right]_{m\times n}$ concerning evaluation indices I_t^E $(t = 1, 2, 3, 4)$ are as follows.

$$\left(\widetilde{\overline{\mathrm{LG}}}\right)^1 = \left[\widetilde{\overline{lg}}_{ij}^1\right]_{3\times 4} = \begin{bmatrix} -0.1490 & 0.6883 & 0.7399 & -0.2729 \\ -0.6360 & 0.2020 & 0.2367 & -0.7253 \\ 0.2136 & 0.9289 & 1.0000 & 0.0821 \end{bmatrix}$$

$$\left(\widetilde{\overline{\mathrm{LG}}}\right)^2 = \left[\widetilde{\overline{lg}}_{ij}^2\right]_{3\times 4} = \begin{bmatrix} 0.4382 & -0.3047 & -0.4380 & 0.5140 \\ 0.9242 & 0.1813 & 0.0480 & 1.0000 \\ 0.2213 & -0.5216 & -0.6549 & 0.2971 \end{bmatrix}$$

$$\left(\widetilde{\overline{\mathrm{LG}}}\right)^3 = \left[\widetilde{\overline{lg}}_{ij}^3\right]_{3\times 4} = \begin{bmatrix} -0.2015 & 0.3432 & 0.6752 & -0.1912 \\ -0.3006 & 0.2320 & 0.5646 & -0.2722 \\ 0.1858 & 0.6819 & 1.0000 & 0.2427 \end{bmatrix}$$

$$\left(\widetilde{\overline{\mathrm{LG}}}\right)^4 = \left[\widetilde{\overline{lg}}_{ij}^4\right]_{3\times 4} = \begin{bmatrix} 0 & -1 & -1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & -1 & 0 \end{bmatrix}$$

As seen from the above calculation results, for the same evaluation index, the same customer's perceived gain or loss are different concerning different PPVS products. As for the same product, the electricity retail company's perceived gain or loss are also different concerning different customers. What's more, for PSL and CCD, there are situations that the loss and gain values equal to zero, indicating that the evaluation indices' AL just reach customers' or company's expectations.

C. CUSTOMERS' AND ELECTRICITY RETAIL COMPANY'S PU MATRICES CONSTRUCTION

Considering customers' perceived disappointment or elation concerning the possible matching results, based on (20) ~ (22), customers' PU matrices $U^l = \left[u_{ij}^l\right]_{m\times n}$ concerning indices I_l^C $(l = 1, 2, 3, 4)$ can be obtained.

$$U^1 = \left[u_{ij}^1\right]_{3\times 4} = \begin{bmatrix} -0.0514 & 0.1087 & 0.1314 & -0.0862 \\ -0.1206 & 0.0385 & 0.0631 & -0.1528 \\ 0.0291 & 0.1791 & 0.2000 & -0.0078 \end{bmatrix}$$

$$U^2 = \left[u_{ij}^2\right]_{3\times 4} = \begin{bmatrix} -0.2000 & 0.0000 & 0.0000 & -0.2000 \\ -0.2000 & 0.0000 & 0.0000 & -0.2000 \\ 0.0000 & 0.2000 & 0.2000 & 0.0000 \end{bmatrix}$$

$$U^3 = \left[u_{ij}^3\right]_{3\times 4} = \begin{bmatrix} -0.0447 & 0.0989 & 0.0640 & -0.0529 \\ -0.0593 & 0.0947 & 0.0267 & -0.1057 \\ 0.0968 & 0.2000 & 0.1632 & 0.1288 \end{bmatrix}$$

$$U^4 = \left[u_{ij}^4\right]_{3\times 4} = \begin{bmatrix} 0.0769 & 0.0878 & 0.1412 & -0.0692 \\ -0.1314 & -0.0293 & 0.0540 & -0.1479 \\ 0.1020 & 0.1525 & 0.2000 & 0.0744 \end{bmatrix}$$

It is the same that the electricity retail company's PU matrices $\widetilde{U}^t = \left[(\widetilde{u})_{ij}^t\right]_{m\times n}$ concerning indices I_t^E $(t = 1, 2, 3, 4)$ can also be calculated based on (20), (21), and (23).

$$\widetilde{U}^1 = \left[(\widetilde{u})_{ij}^1\right]_{3\times 4} = \begin{bmatrix} -0.0327 & 0.1424 & 0.1522 & -0.0591 \\ -0.1323 & 0.0441 & 0.0514 & -0.1494 \\ 0.0466 & 0.1872 & 0.2000 & 0.0182 \end{bmatrix}$$

$$\widetilde{U}^2 = \left[(\widetilde{u})_{ij}^2\right]_{3\times 4} = \begin{bmatrix} 0.0931 & -0.0657 & -0.0931 & 0.1084 \\ 0.1864 & 0.0396 & 0.0107 & 0.2000 \\ 0.0482 & -0.1099 & -0.1360 & 0.0641 \end{bmatrix}$$

$$\widetilde{U}^3 = \left[(\widetilde{u})_{ij}^3\right]_{3\times 4} = \begin{bmatrix} -0.0440 & 0.0737 & 0.1399 & -0.0418 \\ -0.0649 & 0.0504 & 0.1184 & -0.0589 \\ 0.0406 & 0.1411 & 0.2000 & 0.0527 \end{bmatrix}$$

$$\widetilde{U}^4 = \left[(\widetilde{u})_{ij}^4\right]_{3\times 4} = \begin{bmatrix} 0.0000 & -0.2000 & -0.2000 & 0.0000 \\ 0.2000 & 0.0000 & 0.0000 & 0.2000 \\ 0.0000 & -0.2000 & -0.2000 & 0.0000 \end{bmatrix}$$

Further, for different evaluation indices, customers and electricity retail company show different levels of attention. The weight vector of customers' evaluation index set I^C is set as $\omega^C = [0.4,\ 0.25,\ 0.2,\ 0.15]$, and the weight vector of electricity retail company's evaluation index set I^E is set as $\omega^E = [0.3,\ 0.4,\ 0.2,\ 0.1]$. Based on (24) ~ (25), customers' and electricity retail company's comprehensive PU matrices are calculated, as follows.

$$U = \left[u_{ij}\right]_{3\times 4} = \begin{bmatrix} -0.0680 & 0.0764 & 0.0865 & -0.1054 \\ -0.1298 & 0.0300 & 0.0387 & -0.1545 \\ 0.0463 & 0.1845 & 0.1926 & 0.0338 \end{bmatrix}$$

$$\widetilde{U} = \left[\widetilde{u}_{ij}\right]_{3\times 4} = \begin{bmatrix} 0.0187 & 0.0112 & 0.0164 & 0.0173 \\ 0.0419 & 0.0392 & 0.0434 & 0.0434 \\ 0.0414 & 0.0204 & 0.0256 & 0.0417 \end{bmatrix}$$

It is obvious from the calculation results that customers' and the electricity retail company's satisfaction degree concerning the possible matching results are affected by the elation and disappointment perceptions. With the loss and gain value increases, customers and company will obtain more benefits from the products. Thus, the perceived elation and the PU will increase. On the contrary, if the loss and gain value is small, or even become negative, what customers or the company perceived is loss. The stronger the perceived disappointment is, the smaller the PU is.

D. TWO-SIDED MATCHING OPTIMIZATION MODEL SOLVING

Based on the constructed comprehensive PU matrices, according to (26) and (27), by using the linear weighting method, the multi-objective two-sided matching optimization model can be converted to a single-objective optimization model, as follows.

$$\max \bar{U} = 0.5\sum_{i=1}^{3}\sum_{j=1}^{4} u_{ij}x_{ij} + 0.5\sum_{i=1}^{3}\sum_{j=1}^{4} \widetilde{u}_{ij}x_{ij}$$

$$\begin{aligned} s.t.\ & \sum_{i=1}^{3} x_{ij} \le 1, \quad j \in N \\ & \sum_{j=1}^{4} x_{ij} \le 1, \quad i \in M \\ & \sum_{i=1}^{3}\sum_{j=1}^{4} \left(u_{ij} + \widetilde{u}_{ij}\right) x_{ij} \ge -12 \\ & x_{ij} = 0 \text{ or } 1, \quad i \in M, \quad j \in N \end{aligned}$$

By using MATLAB, the optimal matching results can be obtained.

$$x = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

From the above optimal results, customers C_1, C_2, C_3 match with products E_3, E_2, E_1, respectively, and the maximum comprehensive PU is $\bar{U} = 0.2554$.

E. COMPARISON ANALYSIS

1) MATCHING RESULTS COMPARISON WHEN ONLY CONSIDERING NPV AND BENEFIT

To illustrate the effectiveness of considering multiple evaluation indices, the results of this paper are compared with the two-sided matching results when customers only consider NPV and the electricity retail company only considers Benefit, as shown in TABLE 6.

TABLE 6. Two-sided matching results comparison when considering multi-index and single-index.

	C_1	C_2	C_3	$\bar{U}$
multi-index	E_3	E_2	E_1	0.2554
single-index	/	E_2	/	0.0011

As seen from TABLE 6, when only considering NPV and Benefit, only customer C_2 matches successfully, while there is no PPVS product that customers C_1 and C_3 can match with. However, by using the proposed method in this paper, when considering multiple evaluation indices, there are products that all the customers can match with, because C_1 and E_3, C_3 and E_1 have already reached the lowest accepted level of each other concerning each evaluation index. What's more, the comprehensive PU is greater than that when only considering NPV and Benefit. In total, the proposed method in this paper can achieve more successful matching pairs under the premise that the indices reach the lowest accepted levels of customers and company, which will reduce the power quality management costs, and improve both customers' and electricity retail company's satisfaction degree.

2) OPTIMAL MATCHING RESULTS COMPARISON BETWEEN MULTI-OBJECTIVE AND SINGLE-OBJECTIVE

By using the proposed multiple evaluation indices, a single-objective function is established to maximize the customers' PU or the electricity retail company's PU. The matching results and possible investment of customers are compared with the results of the multi-objective optimization model, as shown in TABLE 7.

As seen from TABLE 7, when only taking customers' PU or electricity retail company's PU as the two-sided matching optimization objective, the matching results are different from that of the multi-objective optimization model. Except customer C_2, the investment of customers C_1 and C_3 are greater than that when considering the comprehensive PU of both customers and electricity retail company. The above results show that by considering the PU of both customers and electricity retail company, the multi-objective two-sided matching optimization model can significantly reduce the investment of customers.

3) SENSITIVITY ANALYSIS OF PU TO THE EVALUATION INDEICES

For the sensitivity of customers' PU to the evaluation indices, customer C_1 and product E_3 are taken as an example. When the evaluation indices' EL vary, customer C_1's PU concerning E_3 are plotted in Fig. 6.

Take electricity retail company's PPVS product E_1 as an example, company's PU concerning customer C_3 are shown in Fig. 7 when evaluation indices' EL vary.

As seen from Figs. 6 and 7, all the proposed evaluation indices will have an effect on customers' and company's PU, indicating that only considering NPV and Benefit will lead to inaccurate results. For the cost-type evaluation indices, i.e., IR, VSS, and AVSF, the higher the EL is, the greater the PU is. That is, customers and company will perceive greater benefits. For the benefit-type evaluation indices, i.e., NPV, PSL, IE, Benefit, and CCD, the higher the EL is, the greater

TABLE 7. Comparison of matching results and possible investment of multi-objective optimization and single-objective optimization.

			C_1	C_2	C_3
multi-objective	customers and company	product	E_3	E_2	E_1
		investment($\times 10^4$¥)	86.1937	33.5217	17.8024
single-objective	customers	product	E_4	E_2	E_1
		investment($\times 10^4$¥)	132.8369	33.5217	17.8024
	company	product	E_4	E_2	E_3
		investment($\times 10^4$¥)	132.8369	33.5217	86.1937

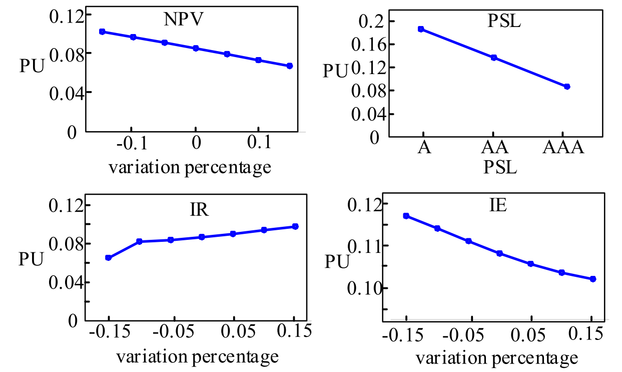

FIGURE 6. The sensitivity of customer C_1's PU to the evaluation indices.

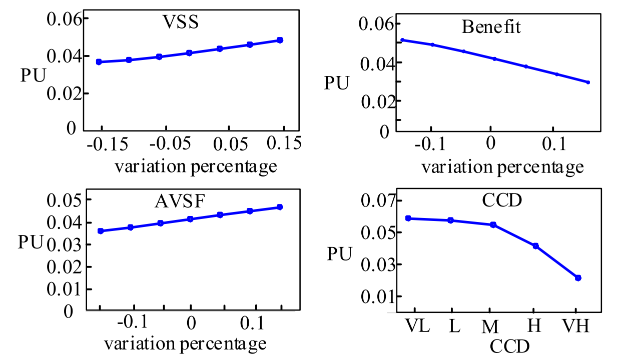

FIGURE 7. The sensitivity of electricity retail company's PU to the evaluation indices.

the deviation degree is, and the lower the PU is. That is, customers and company will perceive greater losses. The above empirical analysis results are in consistent with the theoretical analysis results, indicating the correctness of the proposed method.

4) SENSITIVITY ANALYSIS OF PU TO THE ELATION AND DISAPPOINTMENT PARAMETER

Besides the evaluation index's EL, the elation parameter β and disappointment parameter α will also affect the PU of the customers and company. Take customer C_1, and product E_1 as an example, the sensitivity analysis of PU to β and α are plotted in Fig. 8.

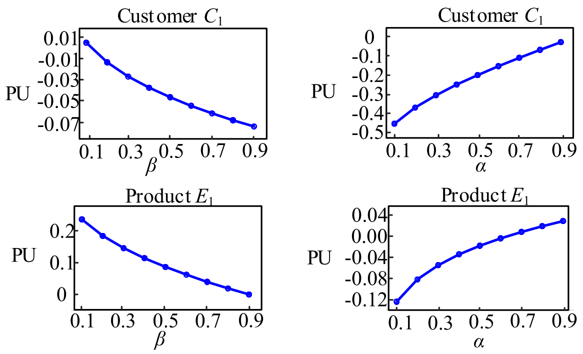

FIGURE 8. The sensitivity analysis of PU to β and α.

As seen from Fig. 8, on one hand, with the increasing of β, both customers' and electricity retail company's PU are decreasing. On the other hand, with the increasing of α, PU are increasing. That is, as for the same gain, the larger the β is, the less elation the customers or the company will perceive. Thus, the PU are smaller. As for the same loss, the larger the α is, the less disappointment the customers or the company will perceive. Thus, the PU are greater.

In total, the main controlling parameters, i.e., the evaluation index's EL, the elation and disappointment parameters, are customer-specific and company-specific. The values of the parameters are all based on customers' and electricity retail company's expectations concerning different indices, and preference and aversion degree concerning loss and gain. As this paper mainly focuses on the PPVS product decision-making process, the details of how to obtain and tune the parameters are not discussed.

F. COMPUTATIONAL EFFICIENCY ANALYSIS

In order to verify the computational efficiency of the proposed method, the calculation time utilized is demonstrated in TABLE 8.

As seen from TABLE 8, the total calculation time of the proposed method is less than 120 seconds. The results show that the proposed method is computationally efficient, which can be used in practical applications. What's more, if more advanced hardware configurations are used, the computational efficiency can be further improved.

TABLE 8. Calculation time of the proposed method.

Iterms	Time(s)
multi-objective two-sided matching optimization model construction	2.78
model solving	107.61
total time	110.39

VIII. MERITS AND LIMITATIONS

In this section, the merits and limitations of the proposed PPVS product decision-making method will be discussed.

Firstly, through the literature review, one can find that existing methods on PPVS product decision-making mainly from the perspective of costs and benefits. For instance, Ghiasi [37] proposed a power quality mitigation solution decision-making method by considering the financial losses due to several critical power quality phenomena, the costs of different mitigation solutions, and the payback owing to the adoption of particular solution. Costs of voltage sag mitigation solutions were taken into account in [36]. Milanovic and Zhang [8] aimed to minimize the global financial losses when choosing the optimal voltage sag mitigation solution with FACTS based devices. Obviously, these studies do not consider the multi-dimensional characteristics when customers evaluate products, and electricity retail companies evaluate customers. Compared with previous studies, besides costs and benefits, this paper investigates multiple qualitative and quantitative evaluation indices characterized by real numbers, interval numbers, linguistic variables and intuitionistic fuzzy numbers, when customers and electricity retail companies make a decision on PPVS products.

Secondly, actually, PPVS product decision-making depends on the matching between customers' PPVS demands and the PPVS levels brought by the products. Although two-sided matching decision-making problems have been widely discussed in marriage matching [15], [16], person-job matching [17], [18], knowledge service matching [19], [20], *et al.*, PPVS demand-level matching has not been fully explored. Although [10] investigated the two-sided matching between customers' PPVS demands and PPVS levels, only NPV and benefit were taken into account. Therefore, it is necessary to construct an optimization model of two-sided matching between customers' PPVS demands and the PPVS levels brought by the products considering multi-dimensional evaluation indices.

Finally, PU is also an important property for the customers and electricity retail company to make a decision due to the fact that elation and disappointment will be perceived concerning different matching results [12]. Although customers' PU for premium power has been discussed in [5], the integration of PU and two-sided matching decision-making on

PPVS product have not been fully investigated. In this paper, PU of both customers and electricity retail company are considered when establishing the matching models. The psychological perceptions of elation and disappointment are taken into account based on disappointment theory. Afterwards, a two-sided matching optimization model that aims to maximize the PU of both sides is constructed. Moreover, an empirical analysis conducted in an industrial park demonstrates the necessity of considering both sides' PU.

Overall, the proposed PPVS product decision-making method based on multi-index two-sided matching enriches the studies of decision-making on PPVS product. However, the approach also has some limitations. On one hand, in this paper, it is assumed that the evaluation indices are expressed by real numbers, interval numbers, linguistic variables and intuitionistic fuzzy numbers, which cannot be used to deal with the situations when customers and electricity retail companies provide more elaborated and complex assessments, such as unbalanced hesitant fuzzy linguistic term sets [38] and distributed linguistic information [39]. On the other hand, in this paper, only three customers and four PPVS products provided by an electricity retail company are considered in the empirical analysis. Although the proposed decision-making method can be scalable in the aspects of the customer number and the product number, as well as the electricity retail company number, with the increasing of the number of customers, products, and electricity retail companies, the resolution to the PPVS product decision-making models may become a little bit complex. In this case, a more efficient model needs to be developed to deal with the PPVS product decision-making problem.

IX. CONCLUSION

A premium power value-added service product decision-making method based on multi-index two-sided matching is proposed in this paper. The conclusions are as follows.

1) The multi-index system with different mathematical and physical attributes is established from the perspective of customers and electricity retail company, and a method of two-sided matching of the customers' PPVS demands and the PPVS levels brought by the products of the electricity retail company is proposed.

2) Considering the difference between the evaluation indices' AL and EL, customers' and electricity retail company's loss and gain matrices are constructed. Furthermore, considering the perceptions of disappointment and elation, PU matrices are established.

3) In order to maximize the comprehensive PU of customers and electricity retail company, a multi-objective two-sided matching optimization model is established, which is transformed into a single-objective optimization model by using linear weighting method.

4) Three large high-tech electronic-based customers located in an industrial park in western Guangdong are investigated and analyzed. The proposed PPVS product decision-making method based on multi-index two-sided matching can improve the accuracy of the results, reduce customers' investment, and maximize the satisfaction degree of both customers and electricity retail company.

Meanwhile, three interesting directions are worth to be further researched.

1) Under the background of the opening of the electricity retail side, PPVS products will become the main focus of customers and electricity retail companies. Not only should the strategy and method of decision-making be studied, but also the legal and policy aspects should be explored.

2) With the further reform of the electricity retail market, more and more customers and electricity retail companies will participate in PPVS products decision-making, which can be regarded as a group decision-making problem. Due to the difference in knowledge and culture background, different decision-makers tend to provide complex and elaborated linguistic expressions with uncertainty. In this case, hesitant fuzzy linguistic information with multiattribute [38] can be a good choice for decision-makers to express the assessments.

3) In practice, two processes are involved in a typical large-scale group decision-making, i.e., the selection process and the consensus process [40]. In 2), the future study in the selection process for PPVS product is discussed. Moreover, consensus reaching also plays an important role in large-scale group decision-making. For example, [41] develops a novel consensus model for a multiattribute group decision-making problem based on multi-granular hesitant fuzzy linguistic term sets. And in order to preserve decision-makers' original preference information as much as possible, the minimum adjustment-based optimization model is proposed. We believe it is very interesting to extend the research results of this study to the large-scale PPVS product group decision-making.

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