

Perceived Utility of Premium Power by High-tech Manufacturers

Yuanqian Ma, Xianyong Xiao, Yang Wang, Ying Wang, and Zixuan Zheng

Abstract—The valuation of premium power based on perceived utility (PU, i.e., perceived effectiveness or satisfaction degree of customers) and their willingness to pay has been researched for years. One of the remaining challenges is the accurate evaluation of PU. PU is the foundation of premium power evaluation, and it is essential for the decision-making process of investments on premium power by high-tech manufacturers (HTMs). This paper presents a framework to effectively evaluate PU. In this framework, factors influencing PU were classified to be quantitative and qualitative. An indication system (IS) was then constructed based on those influencing factors. Finally, PU was evaluated by the IS, considering psychological perception and decision-making behavior of HTMs. The effectiveness of the proposed PU-evaluation framework was demonstrated through field case studies.

Index Terms—Premium power, voltage sag, perceived utility, influencing factors, indication system.

I. INTRODUCTION

THE high penetration of renewable energy and power electronics in modern smart grids makes power quality to be a major concern for both utility providers and customers [1]. Electrical equipment or electronic devices in high-tech manufacturers (HTMs) are very sensitive to poor power quality, especially to voltage sags [2]. An effective way to mitigate the impact of voltage sags is to use premium power [3]. Premium power is supplied to customers who are more sensitive to power quality disturbances. It is normally achieved by using state-of-the-art custom power devices such as uninterruptible power supply device, dynamic voltage regulator, active power filter, etc. [4]–[6].

The concept of premium power and premium power park solutions were studied in [3], [4], premium power control technology was presented in [1], [7], and the optimum in-

vestment for custom power devices were discussed in [8], [9]. However, decision-making processes regarding premium power investments, especially factors that influence the decision-making of customers, have not been well studied. Premium power implies higher costs. Thus, the owner of a high-tech manufacturing company should consider whether it is cost-effective to invest in premium power. A method to assess the economic value of voltage sag mitigation devices was proposed in [8]. A novel idea to value premium power based on perceived utility (PU, i.e., perceived effectiveness or satisfaction degree of customers) and willingness to pay was proposed in [10]. PU is the foundation for evaluating premium power [11]. Therefore, PU can directly affect the decision of HTMs regarding the investments on premium power.

Although the idea in [10] was promising, the insufficient consideration of factors influencing PU could lead to wrong investment decisions. According to the existing investment psychology, investment decision-making behaviors include two stages: judgement, then the actual decision-making [12]. In the first stage, direct costs and benefits, risk preference, and PU are considered. Among them, PU is the most complex factor, which further depends on many influencing factors such as net present value (NPV), voltage sag characteristic (VSC), acceptable power quality (APQ), and others. These influencing factors can be divided into qualitative factors, which are modelled by linguistic variable (LV) and intuitionistic fuzzy number (IFN), and quantitative factors, which are modelled by real number (RN), interval number (IN), and triangular fuzzy number (TFN) [13]. In [10], only two factors were considered, namely expected net benefit (ENB) and voltage sag severity (VSS). Although these two indices have different physical properties (the former is a cost-benefit index and the latter is a power quality index), they were simply added to obtain PU in [10]. This approach is not theoretically coherent. Additionally, despite the same economic loss, the impact of voltage sags on the perceptions of customers can be different because different customers have different expectations. Thus, both expected level (EL) and actual level (AL) of indices should be considered. Conversely, [10] only considered AL and assumed that the VSS of all customers were controlled at the same level.

To address the issues mentioned above, this paper presents a systematic methodology to evaluate PU. An indication system (IS) is developed based on the mathematical modelling of all influencing factors. PU is then evaluated by the frame-

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work, considering the psychological perception and decision-making behavior of electric power customers. The main contributions of this study are as follows.

- 1) Influencing factors that affect PU are investigated comprehensively.
- 2) Influencing factors with different mathematical properties are properly formulated and incorporated into an IS.
- 3) PU is evaluated by the IS. Both AL and EL of evaluation indices are considered as well as the psychological perception and decision-making behavior of HTMs.
- 4) Field case studies are conducted to verify the correctness and effectiveness of the proposed method.

The paper is organized as follows. Section II describes the mathematical modelling of influencing factors and the IS for PU evaluation. Section III illustrates the determination method of the IS. Section IV proposes the PU evaluation method, in which psychological perception and decision-making behavior of HTMs are both considered. Finally, Section V presents a field case study involving five HTMs in a high-tech park in China.

II. PROPOSED IS

The investment decision on premium power is based on a comprehensive evaluation of total costs and benefits. Total costs, including direct and indirect costs, are the sum of installation and operation costs as well as of economic and product losses due to voltage sags. Total benefits measure the satisfaction degree of HTMs. The factors that determine total costs and benefits include NPV, VSC, investment risk (IR), APQ, competency of high-tech manufacturer (CHTM), and investment environment (IE) [14]. These factors have different mathematical properties and can be divided into qualitative and quantitative ones. As shown in Fig. 1, the qualitative ones can be modelled by LV and IFN, and the quantitative ones by RN, IN, and TFN [15].

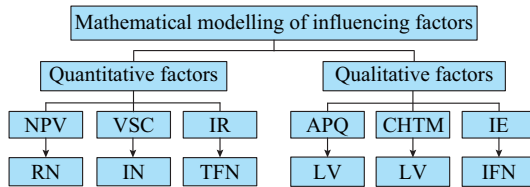


Fig. 1. Mathematical modelling of influencing factors.

The mathematical models of the influencing factors are further discussed as follows.

A. NPV Modelled by RN

From the perspective of HTMs, NPV is an important element [16]. NPV is the difference between the present value of the total annual savings and the initial investment in the premium power [17]. The total annual savings include the reduced voltage sag economic losses and costs of operation and maintenance. The initial investment includes the purchasing and installation costs of the voltage sag mitigation equipment. NPV considers the time value of the premium power investment, which can directly reflect the present value of customers' capital. As a quantitative index, NPV can

be calculated as an RN according to (1).

$$NPV = \sum_{t=0}^m \frac{C_t}{(1+r)^t} - I \quad (1)$$

where r is the annual discount rate; C_t is the savings in the t^{th} year; m is the total number of operation years; and I is the initial investment. NPV is a measure of economic efficiency and validity of the premium power investment [18]. Higher NPV indicates higher probability of the investment in premium power.

B. VSC Modelled by IN

VSC is used to quantify the compatibility between equipment for voltage sag immunity in an HTM and voltage sags occurring in the power grid. According to the IEEE Standard 1564TM-2014 [19], voltage sag magnitude (VSM), voltage sag duration (VSD), VSS, and voltage sag energy (VSE) are the indices needed to characterize a voltage sag. VSM refers to the retained voltage magnitude during a voltage sag, i.e., the lowest root-mean-square (RMS) voltage; VSD is the time that the RMS voltage stays below the threshold; VSS and VSE can be calculated by (2) and (3) as follows. Then, VSC can be modelled as shown in (4).

$$VSS = \frac{1 - VSM}{1 - VSM_{\text{curve}}(VSD)} \quad (2)$$

$$VSE = \left[1 - \left(\frac{VSM}{V_{\text{nom}}} \right)^2 \right] \cdot VSD \quad (3)$$

$$VSC = \{VSM, VSD, VSS, VSE\} \quad (4)$$

where $VSM_{\text{curve}}(VSD)$ is the voltage magnitude value of the Semiconductor Equipment Materials International (SEMI) F47 curve for the same VSD; and V_{nom} is the nominal voltage. SEMI F47 curve is an industry standard curve for voltage sag immunity, i.e. industrial equipment must tolerate voltage sags with specific voltage magnitude and duration [19]. All the above parameters are expressed in per-unit values.

The VSM and VSD tolerance of sensitive equipment varies in a range which can be described by interval data based on the upper and lower thresholds [20]. Thus, the indices in (4) are expressed by IN. Based on historical voltage sag data, VSM, VSD, VSS, and VSE can be calculated by using their definitions as per the IEEE Standard 1564TM-2014. With the aid of the method proposed in [21], i.e., judgement matrix construction, maximum eigenvalue of the judgement matrix calculation, and consistency check, VSC can be determined. Lower VSC indicates higher compatibility between equipment voltage sag immunity and voltage sag, and higher PU of customers.

C. IR Modelled by TFN

IR can be defined as the probability of occurrence of economic losses relative to the expected return on the premium power investment. Due to policy changes, technology upgrading, and enterprise management, HTMs may suffer from benefit reduction or even cost damage.

IR measures the uncertainty level of achieving the returns,

which cannot be described by exact values. Typically, IR fluctuates in a range from the minimum (min) value to the maximum (max) value, from which the most possible value can be estimated. The maximum and minimum values can be obtained through the experience of technicians or by using the method proposed in [22]. Therefore, IR can be described as a TFN by using the fuzzy synthetic evaluation method [23]. Premium power presents a higher potential return than normal power, but it also increases the IR due to higher cost. Thus, IR is an essential influencing factor.

D. APQ Modelled by LV

APQ refers to the acceptable levels of power quality, which can be divided into three levels as:

$$APQ = \{A|AA|AAA\} \quad (5)$$

where A , AA and AAA represent normal-, high- and premium-quality levels, respectively [24]. This index is determined by the equipment type and the equipment's tolerance level towards voltage sags. Lower tolerance levels imply higher need to obtain premium power.

E. CHTMs Modelled by LV

CHTM measures the HTMs' levels of skills, knowledge, and experience on the cognition of premium power and mitigation of power quality problems. CHTM can be divided into five levels and is expressed by

$$CHTM = \{VL|L|M|MG|VG\} \quad (6)$$

where VL , L , M , MG and VG represent very low, low, medium, medium good and very good levels, respectively. This index is determined by the experience of HTMs on voltage sag. Higher CHTMs indicate that they are more likely to invest in premium power.

F. IE Modelled by IFN

IE measures other investment considerations, e.g., natural, social, and legal factors. There are transition states from acceptable (good) to unacceptable (bad) for all these factors. Because IE is uncontrollable for HTMs, normally, intuitionistic fuzzy set theory can be applied, and IE can be expressed by an intuitionistic fuzzy number $\langle u, v \rangle$ [25], where u is called membership degree and represents the degree to which IE is "acceptable (good)", and v is called non-membership degree and represents the degree to which IE is "unacceptable (bad)". These degrees satisfy $0 \leq u + v \leq 1$, and $r = 1 - u - v$ is called the hesitation degree and represents the degree in which IE is between "acceptable (good)" and "unacceptable (bad)". Better IE implies higher investment probability, that is, higher PU towards premium power.

Based on the six influencing factors mentioned above, an IS to evaluate PU is proposed in Fig. 2. As seen in Fig. 2, influencing factors determine two groups of indices, voltage sag and cost-benefit index. The former considers the technology perspective for voltage sags, whereas the latter considers the economic perspective for voltage sags. Voltage sag index is defined as a set of single-event, site, and system indices [19]. This index is determined by VSC, CHTM, and APQ. Cost-benefit index is a set of cost and benefit indices, which are determined by NPV, IR, and IE with different attributes.

Detailed procedures to determine the IS of PU based on influencing factors are presented in the next section.

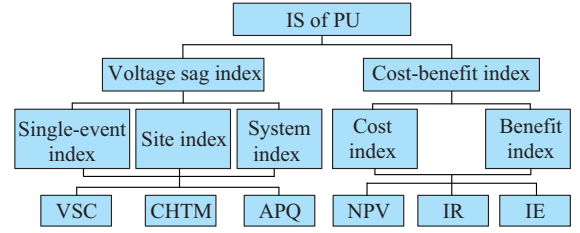


Fig. 2. IS of PU.

III. DETERMINATION METHOD OF IS

Based on the developed IS, the determination method of PU is described in this section. In practice, all influencing factors have their own AL and EL, and there is a deviation between the AL and EL. PU can be then calculated by the following steps. Firstly, the EL and AL of indices are introduced. Then, based on the normalization result of the evaluation indices, the deviation degree between EL and AL can be determined. Finally, the benefits or losses (BOL) perceived by customers are calculated. PU is then evaluated by combining customers' loss aversion and risk aversion psychology. The details are given in the following subsections.

A. EL and AL of Indices

It was assumed that $A = \{A_1, A_2, \dots, A_i, \dots, A_n\}$ is a set of HTMs, where A_i refers to the i^{th} HTM, and n is the number of HTMs. $C = \{c_1, c_2, \dots, c_h, \dots, c_m\}$ is a set of evaluation indices of PU, where c_h is the h^{th} index and could be modelled by RN, IN, TFN, LV and IFN. m is the number of indices. $K = K_1 \cup K_2 \cup K_3 \cup K_4 \cup K_5$ represents different mathematical descriptions, where K_i ($i = 1, 2, \dots, 5$) corresponds to RN, IN, TFN, LV, and IFN, respectively. K_i^b and K_i^c are subsets of K_i , and they represent indices with benefit- and cost-type attributes, respectively, satisfying $K_i^b \cup K_i^c = K_i$ and $K_i^b \cap K_i^c = \emptyset$.

When an HTM decides to invest in premium power, their expectation for the evaluation indices are defined as EL. EL and AL of c_h for A_i are expressed as (7) and (8), respectively.

$$e_{ih} = \begin{cases} d_{ih} & c_h \in K_1 \\ [e_{ihlow}, e_{ihhigh}] & c_h \in K_2 \\ (a_{ih}, b_{ih}, c_{ih}) & c_h \in K_3 \\ S_{ih} \in S_h & c_h \in K_4 \\ \langle \mu_{ih}, \nu_{ih} \rangle & c_h \in K_5 \end{cases} \quad (7)$$

$$r_{ih} = \begin{cases} g_{ih} & c_h \in K_1 \\ [r_{ihlow}, r_{ihhigh}] & c_h \in K_2 \\ (p_{ih}, q_{ih}, t_{ih}) & c_h \in K_3 \\ O_{ih} \in S_h & c_h \in K_4 \\ \langle t_{ih}, f_{ih} \rangle & c_h \in K_5 \end{cases} \quad (8)$$

where d_{ih} and g_{ih} are the EL and AL of the index c_h for A_i when c_h is an RN, respectively; $[e_{ihlow}, e_{ihhigh}]$ and $[r_{ihlow}, r_{ihhigh}]$ are the EL and AL of c_h for A_i when c_h is an IN, respectively; (a_{ih}, b_{ih}, c_{ih}) and (p_{ih}, q_{ih}, t_{ih}) are the EL and AL of c_h for A_i when c_h is a TFN, respectively; S_{ih} and O_{ih} are the EL and

AL of c_h for A_i when c_h is an LV, respectively; $S_h = \{S_{0h}, S_{1h}, \dots, S_{nh}\}$ is the LV set for c_h ; and $\langle \mu_{ih}, v_{ih} \rangle$ and $\langle t_{ih}, f_{ih} \rangle$ are the EL and AL of c_h for A_i when c_h is an IFN, respectively.

B. Normalization of Evaluation Indices

To correctly evaluate PU, e_{ih} in (7) and r_{ih} in (8) should be normalized by the method shown in [15]. Since the evaluation indices have different dimensions, the normalization is essential to eliminate the dimension influence as well as the comparability issue between the indices. The normalization procedure for e_{ih} is shown below, and the procedure for r_{ih} is the same.

1) RN

$$e_{ih} = \begin{cases} d_{ih}/d_{h,\max} & c_h \in K_1^b \\ 1-d_{ih}/d_{h,\max} & c_h \in K_1^c \end{cases} \quad (9)$$

where $d_{h,\max} = \max\{d_{ih} | i = 1, 2, \dots, m\}$.

2) IN

$$e_{ih} = \begin{cases} [e_{ihlow}/e_{hhhigh,\max}, e_{ihhigh}/e_{hhhigh,\max}] & c_h \in K_2^b \\ [1-e_{ihhigh}/e_{hhhigh,\max}, 1-e_{ihlow}/e_{hhhigh,\max}] & c_h \in K_2^c \end{cases} \quad (10)$$

where $e_{hhhigh,\max} = \max\{e_{ihhigh} | i = 1, 2, \dots, m\}$.

3) TFN

$$e_{ih} = \begin{cases} (a_{ih}/c_{h,\max}, b_{ih}/c_{h,\max}, c_{ih}/c_{h,\max}) & c_h \in K_3^b \\ ((1-c_{ih}/c_{h,\max}), 1-b_{ih}/c_{h,\max}, 1-a_{ih}/c_{h,\max}) & c_h \in K_3^c \end{cases} \quad (11)$$

where $c_{h,\max} = \max\{c_{ih} | i = 1, 2, \dots, m\}$.

4) LV

For $e_{ih} = S_{ih} \in S_h$ ($c_h \in K_4$), LV is first converted into a TFN as:

$$e_{ih} = \left(\max\left(\frac{i-1}{n}, 0\right), \frac{i}{n}, \min\left(\frac{i+1}{n}, 1\right) \right) \quad (12)$$

where $i \in \{0, 1, \dots, n\}$. Subsequently, LV is normalized according to (11).

5) IFN

For $e_{ih} = \langle \mu_{ih}, v_{ih} \rangle$ ($c_h \in K_5$), μ_{ih} and v_{ih} vary from 0 to 1. Thus, IFN does not need to be normalized.

C. Deviation Degree Between EL and AL

Typically, there is a deviation between EL and AL which can be characterized by the distance and the sign between normalized EL and AL. The distance indicates the gap between AL and EL. The bigger the distance, the higher the AL deviation from EL, and the higher the impact on the PU and investment decision-making of customers. The distance between AL and EL, denoted by $d(e_{ih}, r_{ih})$, is calculated as follows.

1) If e_{ih} and r_{ih} are RNs,

$$d(e_{ih}, r_{ih}) = d(d_{ih}, g_{ih}) = |d_{ih} - g_{ih}| \quad (13)$$

2) If e_{ih} and r_{ih} are INs,

$$d(e_{ih}, r_{ih}) = d([e_{ihlow}, e_{ihhigh}], [r_{ihlow}, r_{ihhigh}]) = \sqrt{\frac{1}{2}[(e_{ihlow} - r_{ihlow})^2 + (e_{ihhigh} - r_{ihhigh})^2]} \quad (14)$$

3) If e_{ih} and r_{ih} are TFNs,

$$d(e_{ih}, r_{ih}) = d((a_{ih}, b_{ih}, c_{ih}), (p_{ih}, q_{ih}, t_{ih})) = \sqrt{\frac{1}{3}[(a_{ih} - p_{ih})^2 + (b_{ih} - q_{ih})^2 + (c_{ih} - t_{ih})^2]} \quad (15)$$

4) If e_{ih} and r_{ih} are LVs, the distance $d(e_{ih}, r_{ih})$ is then calculated by (15) after e_{ih} and r_{ih} are converted into TFNs through (12).

5) If e_{ih} and r_{ih} are IFNs,

$$d(e_{ih}, r_{ih}) = d(\langle \mu_{ih}, v_{ih} \rangle, \langle t_{ih}, f_{ih} \rangle) = \sqrt{\frac{1}{3}[(\mu_{ih} - t_{ih})^2 + (v_{ih} - f_{ih})^2 + (\pi_{ih} - \gamma_{ih})^2]} \quad (16)$$

where $\pi_{ih} = 1 - \mu_{ih} - v_{ih}$ and $\gamma_{ih} = 1 - t_{ih} - f_{ih}$ are hesitancy degrees of e_{ih} and r_{ih} , respectively.

The sign of the deviation degree indicates whether the premium power will generate a positive or negative effect on HTM. A positive sign means that AL of evaluation index is greater than EL, thereby generating positive PU to the customers. Customers are then more likely to invest in premium power. Conversely, the negative sign means that AL of evaluation index is smaller than EL, thereby generating negative PU to customers. Thus, customers are less likely to invest in premium power. The determination method of the sign is discussed as follows.

1) If e_{ih} and r_{ih} are INs, i.e., $e_{ih} = [e_{ihlow}, e_{ihhigh}]$ and $r_{ih} = [r_{ihlow}, r_{ihhigh}]$, we compute four temporary values through (17) and (18) to identify if $e_{ih} > (or <) r_{ih}$ when $e'_{ih} > (or <) r'_{ih}$, and for $e''_{ih} = r'_{ih}$, if $e_{ih} > (or <) r_{ih}$ when $e''_{ih} < (or >) r''_{ih}$.

$$\begin{cases} e'_{ih} = (e_{ihlow} + e_{ihhigh})/2 \\ e''_{ih} = e_{ihhigh} - e_{ihlow} \end{cases} \quad (17)$$

$$\begin{cases} r'_{ih} = (r_{ihlow} + r_{ihhigh})/2 \\ r''_{ih} = r_{ihhigh} - r_{ihlow} \end{cases} \quad (18)$$

2) When $e_{ih} = (a_{ih}, b_{ih}, c_{ih})$ and $r_{ih} = (p_{ih}, q_{ih}, t_{ih})$ are TFNs, the probability $P(e_{ih} \geq r_{ih})$ is:

$$P(e_{ih} \geq r_{ih}) = \theta \frac{\min(b_{ih} - p_{ih} + q_{ih} - a_{ih}, \max(b_{ih} - p_{ih}, 0))}{b_{ih} - p_{ih} + q_{ih} - a_{ih}} + (1 - \theta) \frac{\min(c_{ih} - q_{ih} + t_{ih} - b_{ih}, \max(c_{ih} - q_{ih}, 0))}{c_{ih} - q_{ih} + t_{ih} - b_{ih}} \quad (19)$$

where θ , within the range (0, 0.5), is the risk aversion coefficient that reflects the risk aversion psychology. If $0.5 \leq P(e_{ih}, r_{ih}) \leq 1$, then $e_{ih} \geq r_{ih}$; and if $0 < P(e_{ih}, r_{ih}) < 0.5$, then $e_{ih} < r_{ih}$.

3) If e_{ih} and r_{ih} are LVs, then $e_{ih} > r_{ih}$ when $S_{ih} \succ O_{ih}$, $e_{ih} < r_{ih}$ when $S_{ih} \prec O_{ih}$, and $e_{ih} = r_{ih}$ when $S_{ih} = O_{ih}$, where the operators $\succ$ and $\prec$ stand for “better than” and “worse than”, respectively, used for non-number settings.

4) If $e_{ih} = \langle \mu_{ih}, v_{ih} \rangle$ and $r_{ih} = \langle t_{ih}, f_{ih} \rangle$ are IFNs, a score function is defined as $S(\alpha) = \mu - v$ and ranges from -1 to 1. Thus, considering IFN $\alpha = \langle \mu, v \rangle$, we obtain $e_{ih} \geq r_{ih}$ for $S(e_{ih}) \geq S(r_{ih})$ and $e_{ih} < r_{ih}$ for $S(e_{ih}) < S(r_{ih})$.

IV. EVALUATION OF PU

Based on the calculated deviation degrees, the BOL for AL relative to EL can be calculated. Then, the PU of HTMs can be evaluated by analyzing psychological perceptions and decision-making behaviors.

A. BOL

The psychological and behavioral characteristics of HTMs typically depend on reference factors [26]. Thus, in this work, by treating EL as a reference, we used the deviation degree between AL and EL to measure perceived BOL, denoted as $\Delta(e_{ih}, r_{ih})$, by:

$$\Delta(e_{ih}, r_{ih}) = \begin{cases} d(e_{ih}, r_{ih}) & r_{ih} \geq e_{ih} \\ -d(e_{ih}, r_{ih}) & r_{ih} < e_{ih} \end{cases} \quad (20)$$

where $d(e_{ih}, r_{ih})$ is the deviation degree function defined in Section III-C.

When AL of an index is greater than EL, the premium power can benefit HTMs. However, if AL is smaller, losses can be perceived by the customers, thus justifying the negative values of $\Delta(e_{ih}, r_{ih})$.

B. PU Evaluation

Different HTMs have different psychological perceptions on the premium power [27], generating different perceived BOL. The obvious difference between the willingness to pay for economic losses due to voltage sags and the willingness to accept the compensation due to voltage sags [28] represents the loss aversion psychology of HTMs [29]. Based on the prospect [26] and cumulative prospect [30] theories, the PU of A_i with $\Delta(e_{ih}, r_{ih})$ BOL is computed as:

$$u(e_{ih}, r_{ih}) = \begin{cases} [\Delta(e_{ih}, r_{ih})]^{1-\theta} & r_{ih} \geq e_{ih} \\ -\lambda[-\Delta(e_{ih}, r_{ih})]^{1-\theta} & r_{ih} < e_{ih} \end{cases} \quad (21)$$

where λ (>1) is the loss aversion coefficient which represents the loss aversion psychology of A_i , which means that the negative feelings from the economic loss would be significantly stronger than the positive feelings from the same amount of economic benefit; and θ ($0 < \theta < 1$) is the relative risk aversion, and it reflects the risk aversion psychology of A_i , e.g., the hesitation of HTM to invest in premium power. λ and θ were determined by survey or expert experience [31]. The final PU is calculated by:

$$u(A_i) = \sum_{h=1}^n u(e_{ih}, r_{ih}) \quad (22)$$

where n is the number of evaluation indices for HTM A_i . The higher the final PU, the more likely A_i is to invest in premium power. The framework of PU evaluation is summarized in Fig. 3.

In Fig. 3, the influencing factors are first modelled by five kinds of mathematical models according to their attributions. Subsequently, the deviation degree between AL and EL of the evaluation indices, and the BOL are calculated. Finally, PU is evaluated based on the prospect and cumulative prospect theories. The flow chart of the PU evaluation is further described in Fig. 4.

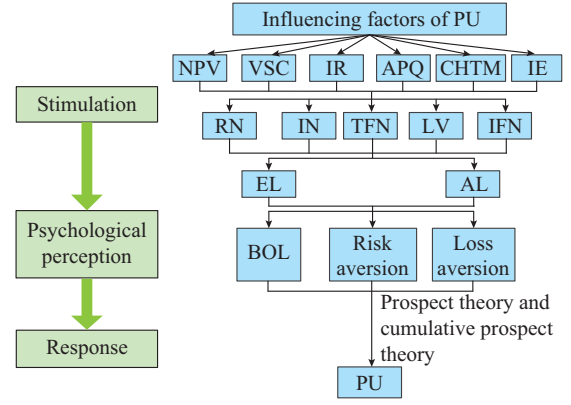


Fig. 3. Framework of PU evaluation.

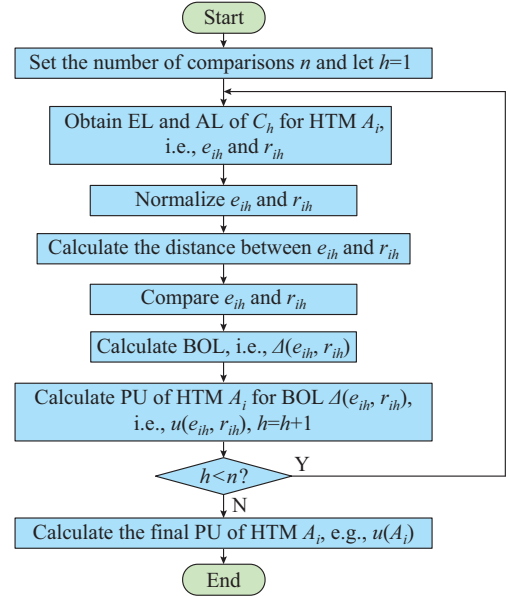


Fig. 4. Evaluation procedures of PU.

V. CASE STUDIES

In this section, field study results are shown to demonstrate the effectiveness of the proposed method. PUs of five HTMs are calculated and compared. The effect of the index's EL variation on the HTMs' PU and the sensitivity of PU to different indices are also studied. Finally, the proposed method is compared with the method in [10] to validate its effectiveness and adaptability.

A. Historical Data Statistics and Parameter Estimation

A field survey is conducted for five HTMs (A_1, A_2, A_3, A_4, A_5) in a high-tech park in Chengdu, China. The map of the surveyed area is shown in Fig. 5. The recorded data of voltage sag events on 10 kV buses for customers A_1 - A_5 from 2007 to 2014 are plotted in Fig. 6.

We statistically analyze the economic losses of the five HTMs from 2007 to 2014. Based on stepwise regression analysis [30] for PU evaluation, we set θ in (19) and λ in (21) as 0.12 and 2.25, respectively.

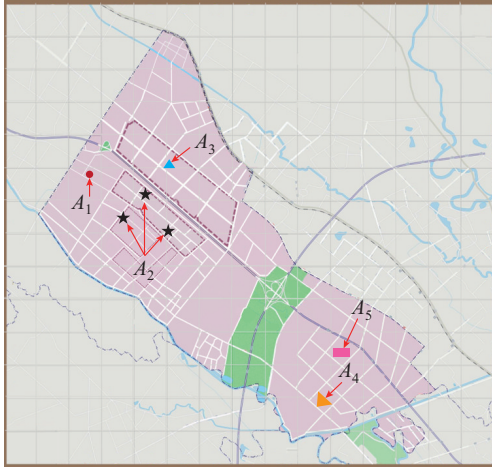


Fig. 5. Surveyed area.

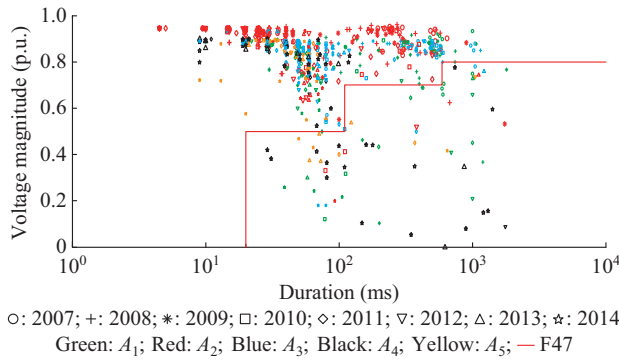


Fig. 6. Recorded data from 2007 to 2014.

B. PU of HTM A_1

Let us take A_1 as an example. Firstly, we obtained ELs and ALs through financial and voltage sag recordings for c_1 - c_6 from 2007 to 2014, as listed in Tables I and II, respectively. Then, based on the obtained values, BOLs of A_1 are computed through (9)-(20), as shown in Table III.

TABLE I
VALUES OF E_{IH} FOR A_1 FROM 2007 TO 2014

Year	NPV	VSC	IR	APQ	CHTM	IE
2007	26.0598	[0,0.765]	(0.40,0.60,0.80)	AA	M	$\langle 0.70,0.25 \rangle$
2008	69.7023	[0,0.469]	(0.60,0.80,1.00)	AA	VG	$\langle 0.70,0.20 \rangle$
2009	46.7749	[0,0.697]	(0.10,0.50,0.60)	AA	MG	$\langle 0.50,0.30 \rangle$
2010	57.8718	[0,0.526]	(0.20,0.60,0.75)	AA	MG	$\langle 0.60,0.30 \rangle$
2011	45.7415	[0,0.834]	(0.30,0.40,0.50)	AA	MG	$\langle 0.50,0.20 \rangle$
2012	67.3574	[0,0.772]	(0.20,0.67,0.80)	AA	MG	$\langle 0.40,0.50 \rangle$
2013	37.0747	[0,0.678]	(0.20,0.50,0.70)	AA	MG	$\langle 0.60,0.20 \rangle$
2014	45.6643	[0,0.867]	(0.10,0.50,0.60)	AA	M	$\langle 0.65,0.20 \rangle$

As shown in Table III, BOLs are different for different evaluation indices. Therefore, different indices have different impacts on the perceived BOL. The higher the BOL, the higher the demand for premium power. BOLs for the APQs from 2007 to 2014 are all zeros because ALs are exactly the same as ELs, i. e., they meet the exact requirements of HTM A_1 .

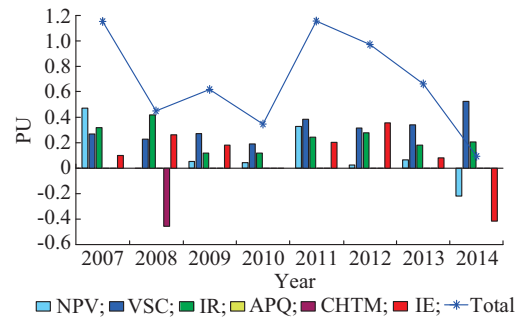
TABLE II
VALUES OF R_{IH} FOR A_1 FROM 2007 TO 2014

Year	NPV	VSC	IR	APQ	CHTM	IE
2007	59.8457	[0.132,0.479]	(0.20,0.30,0.50)	AA	M	$\langle 0.80,0.20 \rangle$
2008	74.8454	[0.183,0.280]	(0.20,0.30,1.00)	AA	MG	$\langle 0.40,0.30 \rangle$
2009	52.7361	[0.167,0.423]	(0.15,0.40,0.50)	AA	MG	$\langle 0.60,0.10 \rangle$
2010	64.1125	[0.113,0.346]	(0.30,0.50,0.80)	AA	MG	$\langle 0.60,0.30 \rangle$
2011	70.0708	[0.257,0.435]	(0.10,0.20,0.30)	AA	MG	$\langle 0.70,0.20 \rangle$
2012	73.4417	[0.156,0.428]	(0.20,0.40,0.50)	AA	MG	$\langle 0.75,0.10 \rangle$
2013	43.1472	[0.237,0.341]	(0.30,0.40,0.50)	AA	MG	$\langle 0.67,0.20 \rangle$
2014	43.7128	[0.152,0.207]	(0.15,0.30,0.40)	AA	M	$\langle 0.50,0.40 \rangle$

TABLE III
VALUES OF $A(e_{ih}, r_{ih})$ (BOL) FOR A_1 FROM 2007 TO 2014

Year	NPV	VSC	IR	APQ	CHTM	IE
2007	0.4257	0.2227	0.2708	0	0	0.0707
2008	0.0000	0.1860	0.3697	0	-0.1633	0.2160
2009	0.0335	0.2269	0.0866	0	0	0.1414
2010	0.0263	0.1503	0.0866	0	0	0.0000
2011	0.2800	0.3356	0.2000	0	0	0.1633
2012	0.0148	0.2671	0.2330	0	0	0.3082
2013	0.0446	0.2913	0.1414	0	0	0.0572
2014	-0.0711	0.4789	0.1658	0	0	-0.1472

Based on Table III, PU of A_1 from 2007 to 2014 can be calculated through (21) and (22). The plotted values are shown in Fig. 7. The PU of BOL is negative for 2008 and 2014 because after the investment on the premium power, AL is smaller than EL, i. e., the investment does not lead to the expected outcome.

Fig. 7. PU of A_1 from 2007 to 2014.

C. Comparative Study

This subsection conducts comparative studies to verify the accuracy and adaptability of the proposed method. Firstly, we compared the PU of five different HTMs. Then, the yearly values of PU, ENB, voltage sag loss (VSL), and the investment for HTM A_1 are compared. The effect of the variation of influencing factors on PU, and the sensitivity of PU to these factors are also analyzed. Finally, the proposed method is compared to that in [10].

1) Comparing PU of different HTMs

By using the proposed method, we obtain the PU of five HTMs, as shown in Fig. 8. The PU of different HTMs vary significantly. Moreover, PU also varies significantly with the years. Particularly, in 2007 and 2011, HTM A_1 suffers from a number of voltage sags resulting in high economic losses. The results indicate that the evaluation results are highly consistent with the actual survey results.

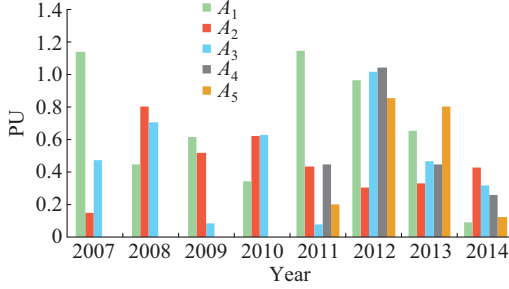


Fig. 8. PU of A_1 - A_5 from 2007 to 2014.

2) Comparing PU, ENB, VSL and investment

Take A_1 as an example again. Firstly, we normalize PU, ENB, VSL, and investment. The results are plotted in Fig. 9.

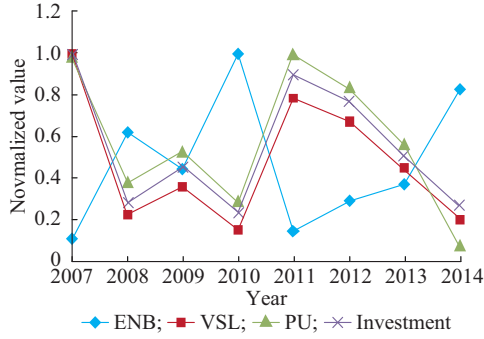


Fig. 9. Comparison of PU, ENB, VSL and investment for A_1 .

As shown in Fig. 9, VSLs are smaller than ENBs in 2008, 2010, and 2014. However, in 2007 and 2011, VSLs are significantly higher than ENBs. Such difference results in a large deviation degree between AL and EL, thereby making PU significant. In the year of 2011, HTM A_1 does have invested in premium power, which supports our results.

3) Variation of influencing factors

By varying the EL of only one influencing factor, we can determine the impact of different influencing factors on the PU. The results are shown in Fig. 10. All influencing factors affect the customers' PU. Such result demonstrates that it is not sufficient to only consider ENB and VSS for an accurate PU evaluation.

4) PU sensitivity to influencing factors

To investigate which influencing factors have larger impact on PU, a sensitivity study was performed based on (23):

$$\eta = \Delta PU / \Delta x \quad (23)$$

where η represents the sensitivity; ΔPU is the variation of PU; and Δx is the variation of an influencing factor. The sensitivity of PU to different influencing factors is shown in

Fig. 11.

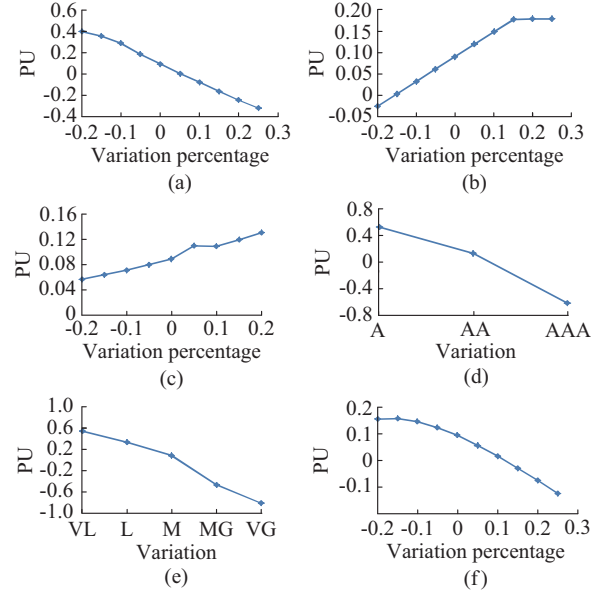


Fig. 10. Relationship between PU and influencing factors. (a) NPV. (b) VSC. (c) IR. (d) APQ. (e) CHTM. (f) IE.

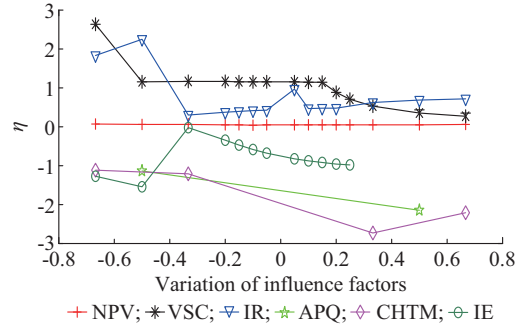


Fig. 11. Sensitivity of PU to influencing factors.

It can be observed from Fig. 11 that PU is more sensitive to the changes of IR, IE, CHTM, and VSC. Therefore, the variation of these four influencing factors have a greater impact on the perception of premium power for customers, and may directly influence the investment.

5) PU comparison with the method only considering ENB and VSS

In [10], PU was calculated from normal and perceived power utilities. The normal power utility and the perceived power utility were characterized by ENB and VSS, respectively. Despite the different physical properties of these two indices, [10] simply adds them to obtain PU. Comparatively, this paper considers influencing factors as well as their attributes in a comprehensive manner, which theoretically leads to a more accurate estimation of PU.

Another important difference is that [10] only considers the AL of the indices and assumes that the VSS of all customers are controlled at the same level, i.e., VSS equals one. When customers encounter severe voltage sags, there are significant economic losses and little benefits. PU in [10] would be very small, thus hindering customers' interest in the premium power. Therefore, PU should only have been

an intermediate variable for investment decision-making. This paper addresses this issue by considering both AL and EL of the indices. This is consistent with the fact that when different customers experience the same VSL, their expectations towards power quality can be different, which leads to different PUs towards the premium power.

By overcoming the two main drawbacks mentioned above, the PU evaluation of this study was significantly improved. Figure 12 and Table IV show the normalized PU obtained by both methods. According to the table, customer A_1 in 2007, A_2 and A_3 in 2010, and A_4 in 2013 (the bolded data in Table IV) suffer from significant economic losses (see VSL). However, the corresponding PUs calculated by [10] are small (all below 0.5), which indicates that there is no urgent need to invest in premium power. In contrast, the PUs obtained by this study are significantly higher. In reality, those customers indeed invest in premium power, thus the values calculated in this study are considered to be more accurate.

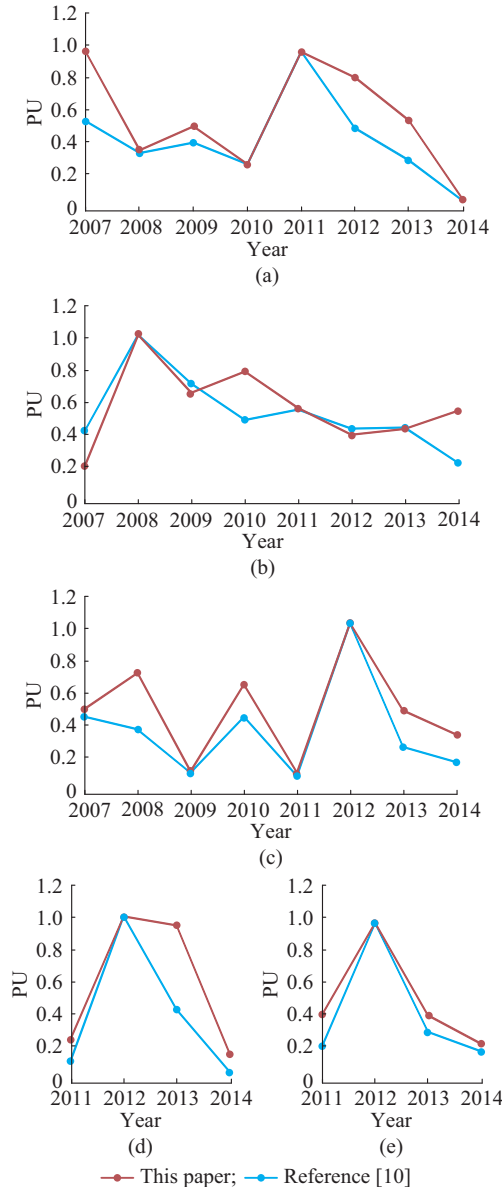


Fig. 12. Normalized PU of five customers by using method presented in this paper and [10]. (a) A_1 . (b) A_2 . (c) A_3 . (d) A_4 . (e) A_5 .

TABLE IV
NORMALIZED PU AND VSL FOR FIVE CUSTOMERS FROM 2007 TO 2014

Year	Item	A_1	A_2	A_3	A_4	A_5
2007	PU in this paper	0.9982	0.1823	0.4675	-	-
	PU in [10]	0.4673	0.4000	0.4214	-	-
	VSL	1.0000	0.1294	0.3269	-	-
2008	PU in this paper	0.3873	1.0000	0.6921	-	-
	PU in [10]	0.3677	1.0000	0.3412	-	-
	VSL	0.2273	0.9892	0.5893	-	-
2009	PU in this paper	0.5340	0.6386	0.0807	-	-
	PU in [10]	0.4340	0.6933	0.0722	-	-
	VSL	0.3636	0.5739	0.1033	-	-
2010	PU in this paper	0.2993	0.7712	0.6207	-	-
	PU in [10]	0.3000	0.4667	0.4201	-	-
	VSL	0.1563	1.0000	0.7416	-	-
2011	PU in this paper	1.0000	0.5408	0.0730	0.2354	0.4306
	PU in [10]	1.0000	0.5333	0.0520	0.1011	0.2315
	VSL	0.7863	0.4397	0.0127	0.1123	0.3977
2012	PU in this paper	0.8402	0.3762	1.0000	1.0000	1.0000
	PU in [10]	0.5246	0.4133	1.0000	1.0000	1.0000
	VSL	0.6745	0.2613	1.0000	0.8796	1.0000
2013	PU in this paper	0.5735	0.4119	0.4587	0.9428	0.4249
	PU in [10]	0.3233	0.4200	0.2315	0.4213	0.3211
	VSL	0.4545	0.3129	0.3198	1.0000	0.3612
2014	PU in this paper	0.0800	0.5265	0.3088	0.1432	0.2481
	PU in [10]	0.0712	0.2000	0.1377	0.0321	0.2012
	VSL	0.2055	0.4013	0.2978	0.0975	0.1301

VI. CONCLUSION

This paper presents a framework to effectively evaluate PU. Compared to the existing method, the proposed method is more accurate because various factors that influence investments are considered, and both AL and EL of evaluation indices are considered. The main conclusions of this study are as follows.

- 1) The factors influencing PU can be classified into qualitative and quantitative ones. By considering these factors, the PU of HTMs can be rationally characterized.
- 2) The BOLs for different indices or the same index in different years are different. The greater the BOL, the higher the willingness to invest.
- 3) Different HTMs with different investment psychologies, anti-risk capabilities, and investment abilities exhibit different sensitivities to influencing factors. The proposed method is adaptable to all HTMs.
- 4) The evaluation results are consistent with the actual survey, which demonstrates the correctness and usefulness of the proposed method.

The investment in the premium power is an important decision for HTMs. Therefore, more practical case studies should be conducted in the future.

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