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Single-Valued Neutrosophic ExpTODIM Technique for Quality Evaluation of MPPT Controller Design for Photovoltaic Systems

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Abstract: The significance of evaluating the design quality of Maximum Power Point Tracking (MPPT) controllers in photovoltaic systems lies in ensuring efficient and stable operation under various environmental conditions. By assessing the controller's tracking efficiency, dynamic response speed, steady-state error, and disturbance rejection capability, the system's energy output can be optimized, equipment lifespan extended, operating costs reduced, and overall system reliability and performance improved, thereby maximizing solar energy utilization efficiency. The quality evaluation of MPPT controller design for photovoltaic systems is framed as a multiple-attribute group decision-making (MAGDM) problem. Recently, the Exponential TODIM (ExpTODIM) approach has been introduced to address this type of decision-making. Single-valued neutrosophic sets (SVNSs) are employed as a decision-making tool to represent fuzzy data during the quality evaluation process of MPPT controller design in photovoltaic systems. In this study, a method combining the single-valued neutrosophic number and Exponential TODIM (SVNN-Com-ExpTODIM), based on the SVNN Hamming distance (SVNNHD) and SVNN Euclidean distance (SVNNED), is proposed to solve the MAGDM problem under SVNSs. Finally, a numerical study is conducted to demonstrate the effectiveness of the SVNN-Com-ExpTODIM approach for the quality evaluation of MPPT controller design in photovoltaic systems, supported by comparative analysis.

Keywords: Multiple-attribute group decision-making (MAGDM); SVNSs; entropy; Exponential TODIM; quality evaluation of MPPT controller design

1. Introduction

The quality evaluation of the Maximum Power Point Tracking (MPPT) controller design for photovoltaic (PV) systems primarily focuses on aspects such as performance, response speed, stability, hardware cost, and applicability. First, tracking accuracy is the fundamental evaluation criterion, which assesses whether the controller can accurately track the maximum power point of the PV cells under varying environmental conditions (such as changes in irradiance and temperature). Secondly, response speed reflects how quickly the controller reacts to external changes, with faster responses maximizing real-time energy output. Stability refers to the controller's performance in continuous operation, where excessive oscillations can lead to energy losses or system instability. The cost-effectiveness of the hardware design is also a key consideration, as the design needs to balance performance with affordability. Advanced algorithms, such as fuzzy control or neural networks, may improve performance but can also increase hardware complexity and cost. Lastly, the applicability of the controller determines its flexibility in being used across different scales and types of PV systems (e.g., grid-tied or standalone systems). Evaluating these factors together provides a comprehensive assessment of the MPPT controller's design quality.

In this study, the SVNN-Com-ExpTODIM approach is proposed to handle MAGDM under SVNSs. To conclude, a numerical study for evaluating the quality of MPPT controller design in photovoltaic systems is conducted to validate the SVNN-Com-ExpTODIM approach through comparative analysis.

The main motivations of this study are as follows:

1. The entropy method is used to determine the weight for SVNSs
2. The SVNN-Com-ExpTODIM approach is proposed for solving MAGDM problems using SVNSs
3. A numerical study is conducted for quality evaluation of MPPT controller design in photovoltaic systems.
4. Several comparisons are made to validate the SVNN-Com-ExpTODIM approach.

The basic structure of this study is outlined as follows. In Sect. 2, the concept of SVNSs is introduced. Sect. 3 presents the SVNN-Com-ExpTODIM approach for addressing MAGDM problems under SVNSs, incorporating the entropy method. Sect. 4 provides a numerical study for the quality evaluation of MPPT controller design in photovoltaic systems, supported by comparative analysis. Finally, concluding remarks are offered in Sect. 5.

2. Literature Review

Early research focused on the design and optimization of MPPT controllers in PV systems. Cao [1] researched the MPPT controller for independent photovoltaic street lighting systems and proposed an improved variable-step optimization algorithm. He designed an MPPT controller based on the LPC2194 microcontroller, and experimental results showed that the algorithm could quickly and accurately track the maximum power point. Gong [2] also studied photovoltaic street lighting systems and proposed an improved maximum power point tracking strategy. He designed both system-level and circuit-level controllers, optimizing the energy utilization of solar panels. As research progressed, Yu and Kang [3] addressed the inefficiency of traditional MPPT techniques under changing environmental conditions. They proposed an MPPT controller based on a lossless power feedback method. Experiments demonstrated that this method significantly improved energy conversion efficiency. Lai [4] further investigated the MPPT controller for small-scale photovoltaic power generation systems, improving the incremental conductance method and battery charging/discharging algorithms. His simulations and experiments confirmed the stability of the control algorithm and the reliability of the system. In the mid-2010s, research began incorporating emerging technologies. Zhong [5] proposed a variable-step perturbation observation method and designed an MPPT controller based on DSP technology. Simulations validated the superiority of the improved algorithm, particularly in tracking performance under various environmental conditions. Zheng [6] combined neural networks, fuzzy controllers, and PID control to propose a neural network fuzzy PID controller. Experiments showed that, compared to traditional PID controllers, this system improved steady-state performance and control accuracy. In the same year, Fu [7] made hardware and software improvements to the MPPT controller by using the incremental conductance method combined with a Buck converter circuit. Experimental results showed a 6.88% increase in maximum power output. Zhang [8] employed a fuzzy PID control algorithm to design a DSP-based MPPT controller for a photovoltaic power generation system. Compared to conventional fuzzy control methods, the fuzzy PID control method exhibited faster tracking speed and better stability, especially under varying light intensity, allowing the system to respond quickly and maintain stability. The most recent study by Fang and Wang [9] designed an MPPT controller based on DC-DC circuits that could quickly and accurately track the maximum power point of photovoltaic power systems, improving the output efficiency of solar cells.

MAGDM is a decision analysis method used when multiple decision-makers evaluate a problem involving multiple attributes or criteria[10-13]. It is typically applied in complex situations where decision-makers, based on their individual experiences, preferences, or expertise, assign scores or rankings to different attributes[14-17]. Each attribute may carry different importance, so weights are often assigned to reflect this. By integrating the opinions of decision-makers and the attribute weights, MAGDM methods help derive the optimal solution or ranking[18-23]. Common methods in MAGDM include the entropy approach [24], fuzzy comprehensive evaluation and TODIM [25, 26]. This approach is widely used in practice, especially in fields requiring the synthesis of diverse opinions, such as technology selection, strategic planning, and policymaking. The quality evaluation of MPPT controller design for photovoltaic systems is a MAGDM problem. Recently, the Exponential TODIM (ExpTODIM) approach [27, 28] has been introduced to address MADM. SVNSs [29, 30] are utilized as a decision-making tool to represent fuzzy data during the quality evaluation of MPPT controller design for photovoltaic systems.

3. **Preliminaries**

Wang et al. [29] conveyed the SVNSs based on the neutrosophic sets[31].

Definition 1 [29]. The SVNSs is conveyed:

$$SA = \left\{ \left(\phi, ST_A(\phi), SI_A(\phi), SF_A(\phi) \right) \middle| \phi \in \Phi \right\} \tag{1}$$

where $ST_A(\phi), SI_A(\phi), SF_A(\phi)$ presents truth-membership, indeterminacy-membership and falsity-membership, $ST_A(\phi), SI_A(\phi), SF_A(\phi) \in [0,1]$ and meets $0 \le ST_A(\phi) + SI_A(\phi) + SF_A(\phi) \le 3$.

The SVNN is conveyed as: $SA = (ST_A, SI_A, SF_A)$, $ST_A, SI_A, SF_A \in [0,1]$, and $0 \le ST_A + SI_A + SF_A \le 3$.

Definition 2 [32]. Let $SA = (ST_A, SI_A, SF_A)$ be SVNN, a score value is conveyed:

$$SV(SA) = \frac{(2 + ST_A - SI_A - SF_A)}{3}, \quad SV(SA) \in [0,1]. \tag{2}$$

Definition 3[32]. Let $SA = (ST_A, SI_A, SF_A)$ be SVNN, accuracy value is conveyed:

$$AV(SA) = \frac{1 + ST_A - SF_A}{2}, \ AV(SA) \in [0,1]. \tag{3}$$

Peng et al. [32] conveyed the order for SVNNs.

Definition 4[32]. Let $SA = (ST_A, SI_A, SF_A)$ and $SB = (ST_B, SI_B, SF_B)$ be SVNNs, $SV(SA) = \frac{(2 + ST_A - SI_A - SF_A)}{3}$ and $SV(SB) = \frac{(2 + ST_B - SI_B - SF_B)}{3}$, and $AV(SA) = \frac{1 + ST_A - SF_A}{2}$ and $AV(ZB) = \frac{1 + ST_B - SF_B}{2}$, then if $SV(SA) < SV(SB)$, then $SA < SB$; if $SV(SA) = SV(SB)$, then (1)if $AV(SA) = AV(SB)$, then $SA = SB$; (2) if $AV(SA) > AV(SB)$, then $SA < SB$.

Definition 5[29]. Let $SA = (ST_A, SI_A, SF_A)$ and $SB = (ST_B, SI_B, SF_B)$ be SVNNs, the operations are conveyed:

(1) $SA \oplus SB = (ST_A + ST_B - ST_A ST_B, SI_A SI_B, SF_A SF_B)$;
(2) $SA \otimes SB = (ST_A ST_B, SI_A + SI_B - SI_A SI_B, SF_A + SF_B - SF_A SF_B)$;
(3) $\lambda SA = \left(1 - (1 - ST_A)^\lambda, (SI_A)^\lambda, (SF_A)^\lambda\right), \lambda > 0$;
(4) $(SA)^\lambda = \left((ST_A)^\lambda, (SI_A)^\lambda, 1 - (1 - SF_A)^\lambda\right), \lambda > 0$.

Definition 6[33]. Let $SA = (ST_A, SI_A, SF_A)$ and $SB = (ST_B, SI_B, SF_B)$, then SVNN Hamming distance (SVNNHD) and SVNN Euclidean distance (SVNNED) are conveyed:

$$SVNNHD(SA, SB) = \frac{|ST_A - ST_B| + |SI_A - SI_B| + |SF_A - SF_B|}{3} \tag{4}$$

$$SVNNED(SA,SB)=\sqrt{\frac{|ST_A-ST_B|^2+|SI_A-SI_B|^2+|SF_A-SF_B|^2}{3}} \quad (5)$$

The SVNNWG approach is conveyed:

Definition 8[32]. Let $SA_j=(ST_j,SI_j,SF_j)$ be SVNNs, the SVNNWG approach is conveyed:

$$\begin{aligned}&\text{SVNNWG}_{sw}(SA_1,SA_2,\ldots,SA_n)\\&=(SA_1)^{sw_1}\otimes(SA_2)^{sw_2},\ldots\otimes(SA_n)^{sw_n}=\mathop{\otimes}_{j=1}^{n}(SA_j)^{sw_j}\\&=\left(\prod_{j=1}^{n}(ST_{ij})^{sw_j},1-\prod_{j=1}^{n}(1-SF_{ij})^{sw_j},1-\prod_{j=1}^{n}(1-ST_{ij})^{sw_j}\right)\end{aligned} \quad (6)$$

where $sw=(sw_1,sw_2,...,sw_n)^T$ be weight of SA_j, $sw_j>0,\sum_{j=1}^{n}sw_j=1$.

4. The proposed model

4.1. SVNN-MAGDM information

The SVNN-Com-ExpTODIM approach is conveyed for MAGDM. Let $SA=\{SA_1,SA_2,\cdots,SA_m\}$ be alternatives, and $SG=\{SG_1,SG_2,\cdots,SG_n\}$ be attributes with weight $s\omega$, where $s\omega_j\in[0,1]$, $\sum_{j=1}^{n}s\omega_j=1$ and invited experts $SE=\{SE_1,SE_2,\cdots,SE_q\}$ with expert's weight $sw=\{sw_1,sw_2,\cdots,sw_t\}$, where $sw_j\in[0,1]$, $\sum_{k=1}^{t}sw_k=1$. Then, SVNN-Com-ExpTODIM approach is conveyed for MAGDM.

(1). Expound the SVNN-matrix $SM^t=\left[SM_{ij}^t\right]_{m\times n}=\left(ST_{ij}^t,SI_{ij}^t,SF_{ij}^t\right)_{m\times n}$ and average matrix $SM=\left[SM_{ij}\right]_{m\times n}$:

$$SM^t=\left[SM_{ij}^t\right]_{m\times n}=\begin{array}{c}\\SA_1\\SA_2\\\vdots\\SA_m\end{array}\begin{array}{c}\begin{array}{cccc}SG_1&SG_2&\ldots&SG_n\end{array}\\\begin{bmatrix}SM_{11}^t&SM_{12}^t&\ldots&SM_{1n}^t\\SM_{21}^t&SM_{22}^t&\ldots&SM_{2n}^t\\\vdots&\vdots&\vdots&\vdots\\SM_{m1}^t&SM_{m2}^t&\ldots&SM_{mn}^t\end{bmatrix}\end{array} \quad (7)$$

$$SM=\left[SM_{ij}\right]_{m\times n}=\begin{array}{c}\\SA_1\\SA_2\\\vdots\\SA_m\end{array}\begin{array}{c}\begin{array}{cccc}SG_1&SG_2&\ldots&SG_n\end{array}\\\begin{bmatrix}SM_{11}&SM_{12}&\ldots&SM_{1n}\\SM_{21}&SM_{22}&\ldots&SM_{2n}\\\vdots&\vdots&\vdots&\vdots\\SM_{m1}&SM_{m2}&\ldots&SM_{mn}\end{bmatrix}\end{array} \quad (8)$$

Based on SVNNWG, the $SM = \left[SM_{ij} \right]_{m \times n} = \left(ST_{ij}, SI_{ij}, SF_{ij} \right)_{m \times n}$ is conveyed:

$$SM_{ij} = \otimes_{k=1}^{t} \left(SM_{ij}^{k} \right)^{sw_k} = \left(1 - \prod_{k=1}^{t} \left(ST_{ij}^{t} \right)^{sw_k}, \prod_{k=1}^{t} \left(SI_{ij}^{t} \right)^{sw_k}, \prod_{k=1}^{t} \left(SF_{ij}^{t} \right)^{sw_k} \right) \tag{9}$$

(2). Normalize the $SM = \left[SM_{ij} \right]_{m \times n} = \left(ST_{ij}, SI_{ij}, SF_{ij} \right)_{m \times n}$ into $SM^{N} = \left[SM_{ij}^{N} \right]_{m \times n} = \left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right)_{m \times n}$.

For benefit attributes:

$$SM_{ij}^{N} = \left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) = \left(ST_{ij}, SI_{ij}, SF_{ij} \right) \tag{10}$$

For cost attributes:

$$SM_{ij}^{N} = \left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) = \left(SF_{ij}, SI_{ij}, ST_{ij} \right) \tag{11}$$

4.2. Compute the attributes weight by entropy.

Entropy [24] is conveyed the weight. The matrix SS_{ij} is conveyed:

$$SS_{ij} = \frac{\left(SV\left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) + AV\left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) + 2 \right)}{\sum_{i=1}^{m} \left(SV\left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) + AV\left(ST_{ij}^{N}, SI_{ij}^{N}, SF_{ij}^{N} \right) + 2 \right)}, \tag{12}$$

The neutrosophic Shannon entropy (NSE) is conveyed:

$$NSE_{j} = -\frac{1}{\ln m} \sum_{i=1}^{m} SS_{ij} \ln SS_{ij} \tag{13}$$

and $SS_{ij} \ln SS_{ij} = 0$ if $SS_{ij} = 0$.

Then, the weight information is conveyed:

$$s\omega_{j} = \frac{1 - NSE_{j}}{\sum_{j=1}^{n} \left(1 - NSE_{j} \right)}, \quad j = 1, 2, \cdots, n. \tag{14}$$

4.3. SVNN-Com-ExpTODIM approach for MAGDM

The SVNN-Com-ExpTODIM approach is conveyed to solve MAGDM.

(1) Expound relative weight:

$$rs\omega_{j} = s\,\omega_{j} \Big/ \max_{j} s\omega_{j}, \tag{15}$$

(2) The neutrosophic dominance degree (NDD) of SA_i over SA_t for SG_j is conveyed in light with SVNNHD and SVNNED:

$$NDD_j\left(SA_i,SA_t\right)=\begin{cases}\frac{1}{2}\left(\frac{rs\omega_j\times\left(1-10^{-\rho DVNNHD\left(SM_{ij}^N,SM_{tj}^N\right)}\right)}{\sum_{j=1}^{n}rs\omega_j}+\frac{rs\omega_j\times\left(1-10^{-\rho DVNNED\left(SM_{ij}^N,SM_{tj}^N\right)}\right)}{\sum_{j=1}^{n}rs\omega_j}\right) & \text{if } SV\left(SM_{ij}^N\right)>SV\left(SM_{tj}^N\right)\\ 0 & \text{if } SV\left(SM_{ij}^N\right)=SV\left(SM_{tj}^N\right)\\ \frac{1}{2}\left(-\frac{1}{s\theta}\frac{\sum_{j=1}^{n}rs\omega_j\times\left(1-10^{-\rho DVNNHD\left(SM_{ij}^N,SM_{tj}^N\right)}\right)}{rs\omega_j}-\frac{1}{s\theta}\frac{\sum_{j=1}^{n}rs\omega_j\times\left(1-10^{-\rho DVNNED\left(SM_{ij}^N,SM_{tj}^N\right)}\right)}{rs\omega_j}\right) & \text{if } SV\left(SM_{ij}^N\right)<SV\left(SM_{tj}^N\right)\end{cases}$$

(16)

where $s\theta$ and $\rho\in[1,5]$ is from [27].

The $NDD_j\left(SA_i\right)$ for SG_j is conveyed:

$$NDD_j\left(SA_i\right)=\left[NDD_j\left(SA_i,SA_t\right)\right]_{m\times m}$$

$$=\begin{matrix} & SA_1 & SA_2 & \cdots & SA_m\\ \begin{matrix}SA_1\\SA_2\\\vdots\\SA_m\end{matrix} & \multicolumn{4}{l}{\begin{bmatrix}0 & NDD_j\left(SA_1,SA_2\right) & \cdots & NDD_j\left(SA_1,SA_m\right)\\ NDD_j\left(SA_2,SA_1\right) & 0 & \cdots & NDD_j\left(SA_2,SA_m\right)\\ \vdots & \vdots & \cdots & \vdots\\ NDD_j\left(SA_m,SA_1\right) & NDD_j\left(SA_m,SA_2\right) & \cdots & 0\end{bmatrix}}\end{matrix}$$

(3) Expound the $NDD\left(SA_i,SA_t\right)$ of SA_i over other alternatives:

$$NDD\left(SA_i,SA_t\right)=\sum_{j=1}^{n}NDD_j\left(SA_i,SA_t\right) \tag{17}$$

The $NDD=NDD\left(SA_i,SA_t\right)_{m\times m}$ is conveyed:

$$NDD = NDD\left(SA_i, SA_t\right)_{m\times m}$$

$$= \begin{bmatrix} & SA_1 & SA_2 & \cdots & SA_m \\ SA_1 & \sum_{j=1}^{n} NDD_j\left(SA_1, SA_1\right) & \sum_{j=1}^{n} NDD_j\left(SA_1, SA_2\right) & \cdots & \sum_{j=1}^{n} NDD_j\left(SA_1, SA_m\right) \\ SA_2 & \sum_{j=1}^{n} NDD_j\left(SA_2, SA_1\right) & \sum_{j=1}^{n} NDD_j\left(SA_2, SA_2\right) & \cdots & \sum_{j=1}^{n} NDD_j\left(SA_2, SA_m\right) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ SA_m & \sum_{j=1}^{n} NDD_j\left(SA_m, SA_1\right) & \sum_{j=1}^{n} NDD_j\left(SA_m, SA_2\right) & \cdots & \sum_{j=1}^{n} NDD_j\left(SA_m, SA_m\right) \end{bmatrix}$$

(4) Expound the overall $NDD\left(SA_i\right)$ of SA_i:

$$NDD\left(ZA_i\right) = \frac{\sum_{t=1}^{m} NDD\left(SA_i, SA_t\right) - \min_i \left\{ \sum_{t=1}^{m} NDD\left(SA_i, SA_t\right) \right\}}{\max_i \left\{ \sum_{t=1}^{m} NDD\left(SA_i, SA_t\right) \right\} - \min_i \left\{ \sum_{t=1}^{m} NDD\left(SA_i, SA_t\right) \right\}}. \quad (18)$$

(5) Sort and select the optimal alternative with $NDD\left(SA_i\right)$, the greater $NDD\left(SA_i\right)\left(i = 1, 2, \cdots, m\right)$ is better choice.

5. Results and Discussion

5.1. Case Study

The MPPT controller in a photovoltaic system is a key component that ensures efficient operation under varying environmental conditions. The design quality of the MPPT controller is directly related to the energy output, stability, and long-term reliability of the photovoltaic system as shown in Figure 1. Therefore, it is essential to conduct a quality evaluation of the MPPT controller's design. The core function of the MPPT controller is to continuously adjust the operating point through algorithms so that the photovoltaic system can produce maximum power at any given time. In practical applications, factors such as solar irradiance and ambient temperature are constantly changing, which place high demands on the controller's response speed and tracking accuracy. Quality evaluation allows us to measure the controller's performance under various conditions, ensuring that it operates optimally in the photovoltaic system. The primary objective of evaluating the design quality of an MPPT controller is to assess its performance under different working conditions using quantifiable indicators.

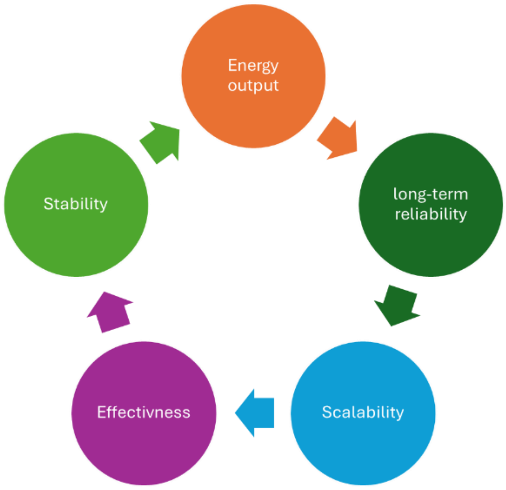

Figure 1. The design quality of MPPT.

Common evaluation metrics include tracking efficiency, dynamic response speed, steady-state error, and disturbance rejection capability as shown in Figure 2. These metrics represent the controller's accuracy in tracking the maximum power point, its speed in responding to changes, its stability during long-term operation, and its ability to handle external disturbances. Tracking efficiency measures the controller's ability to accurately follow the maximum power point of the photovoltaic system under varying environmental conditions. It is usually expressed as a percentage, ideally close to 100%, to maximize power generation efficiency.

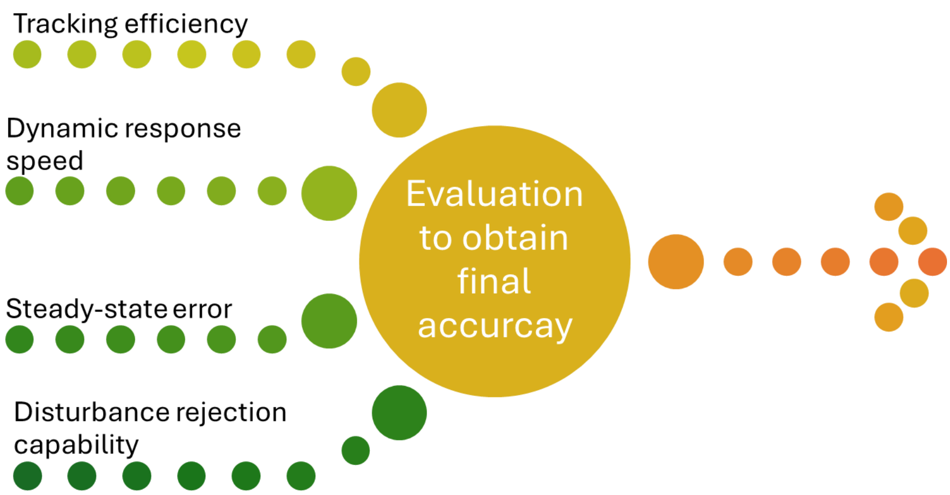

Figure 2. The evaluation metrics of MPPT.

Dynamic response speed evaluates the controller's ability to quickly adjust and find the new maximum power point when external conditions change. The faster the response, the less energy is lost. Steady-state error indicates the deviation between actual output and the maximum power point after long-term operation, the smaller the error, the higher the overall system efficiency. Disturbance rejection capability reflects the controller's ability to swiftly recover and maintain operation near the maximum power point in the face of load fluctuations or external interference. In addition to the quantitative analysis of these technical indicators, the economic viability and applicability of the system must also be considered during the MPPT controller's quality evaluation. For example, the controller should offer a high cost-performance ratio and be adaptable to various types of photovoltaic systems and installation environments. Furthermore, the controller's reliability and durability are critical factors, especially in long-term operation and harsh environments, where the controller must work stably to reduce maintenance costs. A comprehensive evaluation of the MPPT controller's design quality not only helps manufacturers optimize product design but also provides users with a scientific basis for selecting the right controller. Ultimately, a high-quality MPPT controller can maximize the energy output of the photovoltaic system, extend equipment lifespan, reduce overall maintenance and operational costs, and improve the system's overall economic efficiency and sustainability. The quality evaluation of MPPT controller design for photovoltaic systems is MAGDM. Five MPPT controller design schemes for photovoltaic systems $SA_i\ (i=1,2,3,4,5)$ are conveyed with different attributes (See Table 1).

Table 1. Four attributes for quality evaluation of MPPT controller design for photovoltaic systems

Attributes	Attribute Description
SG_1- Tracking Efficiency	Tracking efficiency measures how accurately the MPPT controller can track the maximum power point (MPP) of the photovoltaic system. It is usually expressed as a percentage, ideally close to 100%. Improving tracking efficiency maximizes the energy output of the system.
SG_2-Dynamic Response Speed	Dynamic response speed refers to how quickly the MPPT controller can adjust and find the new maximum power point when environmental conditions (such as sunlight or temperature) change. A fast dynamic response helps maintain high energy output under changing conditions.
SG_3-Steady-State Error	Steady-state error indicates the deviation between the actual power and the maximum power point after the MPPT controller has been running for an extended period. A lower steady-state error means the controller can operate stably near the maximum power point, improving overall system performance.
SG_4-Disturbance Rejection Capability	Disturbance rejection capability measures how well the MPPT controller can quickly recover and maintain maximum power point operation when facing external disturbances (such as load changes or external interference). Excellent disturbance rejection capability ensures the system's stability and reliability under various complex conditions.

Five MPPT controller design schemes for photovoltaic systems are evaluated in light with linguistic scales through four attributes and three experts $SE_t\ (t=1,2,3)$ with expert's weight $sw=(1/3,1/3,1/3)$.

The SVNN-Com-ExpTODIM approach is conveyed to solve the quality evaluation of MPPT controller design for photovoltaic systems.

Step 1. Build the decision matrix $SM^t = \left[SM_{ij}^t\right]_{5\times4} = \left(ST_{ij}^t, SI_{ij}^t, SF_{ij}^t\right)_{5\times4}$ and according to SVNNWG approach, the $SM = \left[SM_{ij}\right]_{5\times4}$ is conveyed as shown in Table 2

Step 2. Normalize the decision matrix as shown in Table 3.

Step 3. Expound the weights as shown in Figure 3.

Step 4. Expound the relative weights as shown in Figure 3.

Step 5. Expound the $NDD = NDD\left(SA_i, SA_t\right)_{5\times5}$ as shown in Table 4.

Step 6. Expound the $NDD\left(SA_i\right)\left(i = 1, 2, \cdots, 5\right)$ as shown in Figure 4.

Step 7. Conclusively, the order is conveyed: $SA_2 \succ SA_4 \succ SA_5 \succ SA_3 \succ SA_1$, and thus the optimal MPPT controller design scheme for photovoltaic systems is SA_2.

Table 2. The aggregated decision matrix

	SG_1	SG_2	SG_4	SG_3
SA_1	(0.8643, 0.0721, 0.0636)	(0.4910, 0.3035, 0.2055)	(0.7321, 0.1345, 0.1863)	(0.5812, 0.2440, 0.2558)
SA_2	(0.5382, 0.3210, 0.1408)	(0.6003, 0.2110, 0.1887)	(0.6423, 0.1927, 0.1650)	(0.7546, 0.1234, 0.1220)
SA_3	(0.4659, 0.2947, 0.2394)	(0.7396, 0.1225, 0.1379)	(0.5730, 0.2874, 0.1396)	(0.8103, 0.1135, 0.0762)
SA_4	(0.5793, 0.2714, 0.1493)	(0.6477, 0.1850, 0.1673)	(0.6891, 0.2017, 0.1092)	(0.7284, 0.1583, 0.1133)
SA_5	(0.7564, 0.1740, 0.0696)	(0.5902, 0.2309, 0.1789)	(0.8110, 0.1055, 0.0835)	(0.6921, 0.2043, 0.1036)

Table 3. The normalized decision matrix

	SG_1	SG_2	SG_4	SG_3
SA_1	(0.8643, 0.0721, 0.0636)	(0.4910, 0.3035, 0.2055)	(0.7321, 0.1345, 0.1863)	(0.5812, 0.2440, 0.2558)
SA_2	(0.5382, 0.3210, 0.1408)	(0.6003, 0.2110, 0.1887)	(0.6423, 0.1927, 0.1650)	(0.7546, 0.1234, 0.1220)
SA_3	(0.4659, 0.2947, 0.2394)	(0.7396, 0.1225, 0.1379)	(0.5730, 0.2874, 0.1396)	(0.8103, 0.1135, 0.0762)
SA_4	(0.5793, 0.2714, 0.1493)	(0.6477, 0.1850, 0.1673)	(0.6891, 0.2017, 0.1092)	(0.7284, 0.1583, 0.1133)
SA_5	(0.7564, 0.1740, 0.0696)	(0.5902, 0.2309, 0.1789)	(0.8110, 0.1055, 0.0835)	(0.6921, 0.2043, 0.1036)

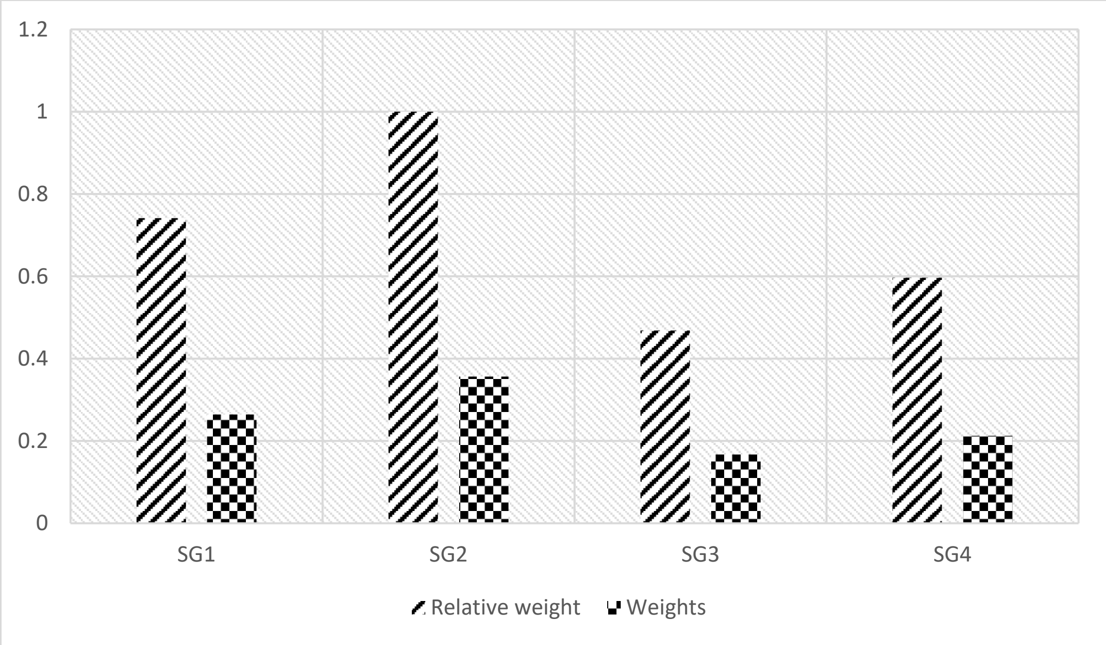

Figure 3. The weights and relative weights or criteria.

Table 4. The NDD.

Alternatives	SA_1	SA_2	SA_3	SA_4	SA_5
SA_1	0.0000	-2.8637	3.0170	2.4587	-3.8237
SA_2	-0.3372	0.0000	2.9214	-1.1111	-1.5806
SA_3	-3.3360	1.6102	0.0000	2.1658	-1.4228
SA_4	0.2667	-3.3769	3.5632	0.0000	-1.0893
SA_5	0.2454	-0.4505	-0.0180	-0.4167	0.0000

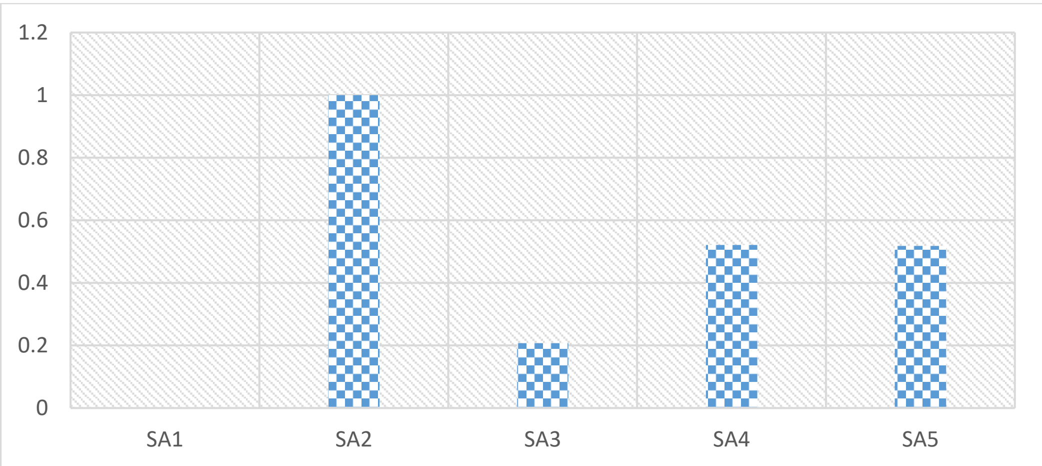

Figure 4. The SVNNDD values.

5.2. Comparative analysis

The SVNN-Com-ExpTODIM is compared with SVNNWA approach [32] and SVNNWG approach[32], SVNN-CODAS approach [34], SVNN-EDAS approach [35], SVNN-TOPSIS approach [36] and SVNN-TODIM approach [37]. The final comparative order is conveyed in Figure 5.

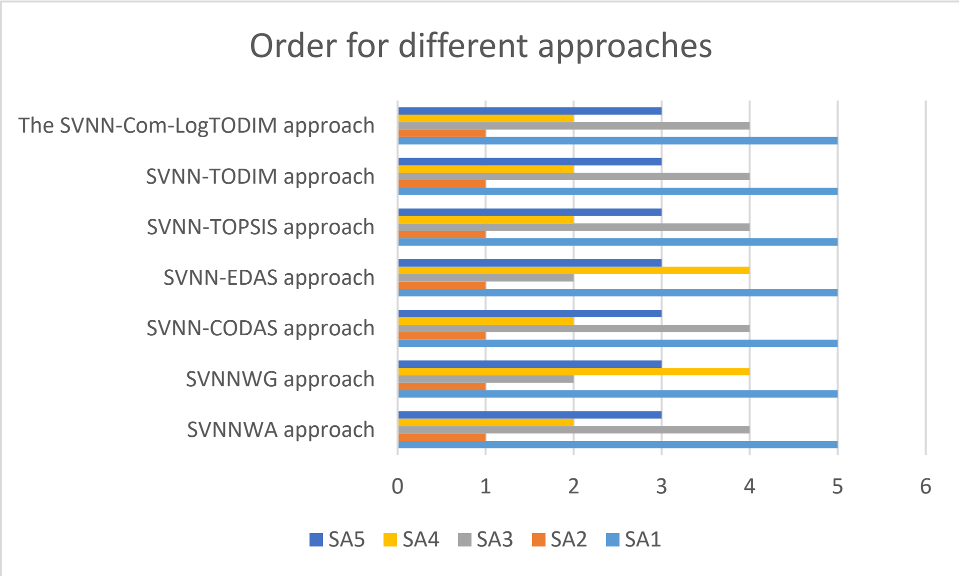

Figure 5. Order for different approaches

From detailed analysis, it could be conveyed that order of these approaches is slightly different, however, these approaches have same optimal MPPT controller design scheme for photovoltaic systems and worst MPPT controller design scheme for photovoltaic systems. This conveyed the SVNN-Com-ExpTODIM is effective.

In comparison with existing methods, the SVNN-Com-ExpTODIM method proposed in this paper demonstrates significant advantages, making it more effective and robust when evaluating the design quality of MPPT controllers in photovoltaic systems. Three key advantages of the proposed approach are conveyed:

(1) Stronger ability to handle uncertainty: The SVNN-Com-ExpTODIM method integrates SVNNs with the Exponential TODIM theory, and by introducing the SVNNHD and SVNNED, it can more accurately handle uncertainty and fuzzy data. This allows the method to better capture the fuzziness and uncertainty in complex decision-making problems, resulting in more accurate and reliable evaluation outcomes.

(2) Effectively considers decision-makers' behavior preferences: The SVNN-Com-ExpTODIM method, through the exponential version of the TODIM model, is better equipped

to model different decision-makers' behavior preferences, especially risk-averse and risk-seeking behaviors. This enables the method to adjust the decision-making process based on varying decision-makers' attitudes, providing ranking results that align more closely with real-world decision-making scenarios, and enhancing the method's flexibility in group decision-making.

(3) Adaptability to complex environmental conditions: The SVNN-Com-ExpTODIM method demonstrates better adaptability in dynamic environments, effectively handling complex conditions common in photovoltaic systems (such as sunlight variation and temperature fluctuations). Compared to existing methods, this approach comprehensively considers multiple environmental factors, ensuring stable evaluation results across different scenarios, thus improving the effectiveness of MPPT controller design quality assessments.

5.3. Sensitivity analysis

Inspired through sensitivity analysis methodology described in [38], an extensive investigation is carried out to evaluate how changes in parameter values influence the performance of the SVNN-Com-ExpTODIM method. This analysis is performed for two distinct DMs behavioral profiles: one characterized by risk aversion and the other by risk seeking. The parameter values used in the analysis are varied within the range of [1, 5]. A comprehensive summary of the sensitivity analysis results can be found in Figure 6.

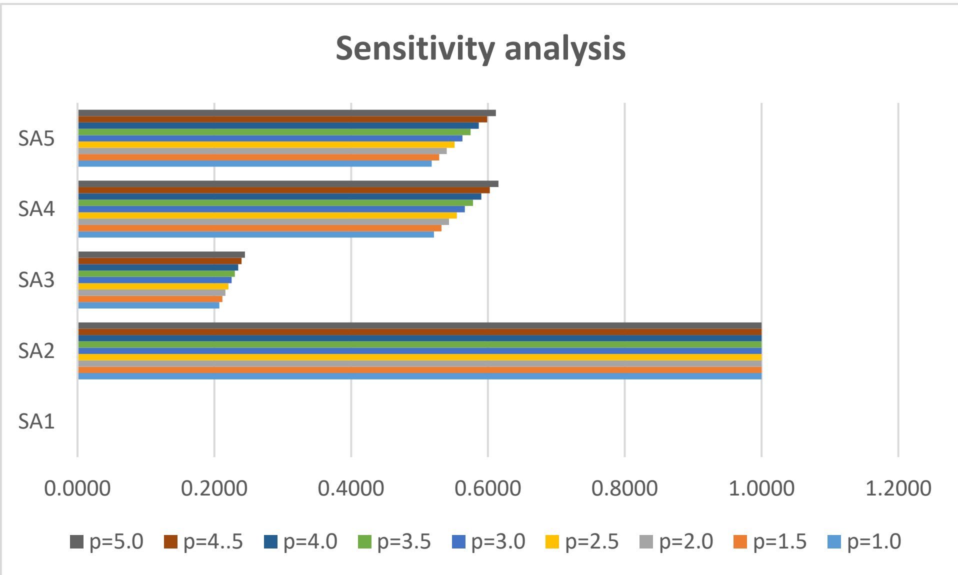

Figure 6. NDD for different ρ

6. Conclusion

The primary purpose of evaluating the design quality of MPPT controllers in photovoltaic systems is to ensure that the system can effectively track the maximum power point under varying environmental conditions, thereby maximizing the energy output of solar power generation. By assessing key indicators such as tracking efficiency, dynamic response speed, steady-state error, and disturbance rejection capability, the controller's design and tuning can be optimized to ensure efficient and stable performance in real-world applications. A high-quality MPPT controller not only enhances the overall power generation efficiency of the photovoltaic system but also maintains stable operation under complex weather conditions, minimizing energy loss. Furthermore, evaluating the controller's design quality helps prevent potential failures, extends the equipment's lifespan, and reduces maintenance and operating costs. Ultimately, this evaluation lays the foundation for ensuring the long-term reliability and cost-effectiveness of photovoltaic systems, contributing to the overall improvement of solar power generation efficiency. The quality evaluation of MPPT controller design for photovoltaic systems is considered a MAGDM problem. In this context, the ExpTODIM approach is introduced to address the MAGDM. Specifically, SVNSs are utilized as a decision-making tool to represent fuzzy data during the quality evaluation process. This study proposes the SVNN-Com-ExpTODIM approach to solve the MAGDM problem under SVNSs. To validate this approach, a numerical study for the quality evaluation of MPPT controller design in photovoltaic systems is conducted, supported by comparative analysis. The key research motivations of this study are as follows: (1) The entropy method is applied to determine the weight for SVNSs; (2) The SVNN-Com-ExpTODIM approach is proposed to solve the MAGDM under SVNSs; (3) A numerical study for the quality evaluation of MPPT controller design is conducted; and (4) Several comparisons are made to validate the effectiveness of the SVNN-Com-ExpTODIM approach.

Although the SVNN-Com-ExpTODIM method proposed in this paper demonstrates a certain degree of innovation and effectiveness in evaluating the design quality of MPPT controllers in photovoltaic systems, there are still some shortcomings. In future research, these limitations can be addressed through improvements, and new research directions can be explored. Below are the research deficiencies in this paper and potential future research directions: (1) Limitations of Parameter Sensitivity Analysis: While the paper conducts a sensitivity analysis regarding parameter variations, the range of parameters analyzed is relatively narrow (limited to the [1, 5] interval). This restricted range may not be sufficient to fully evaluate all potential impacts of parameter variations on model performance, especially in more complex photovoltaic systems or under extreme environmental conditions. (2) Insufficient Consideration of Dynamic Environmental Diversity: The operating environment of photovoltaic systems is complex and variable. In actual applications, fluctuations in environmental factors (such as sunlight intensity, temperature changes, etc.) can significantly affect the performance of MPPT controllers. The model presented in this paper does not fully capture the diversity of such dynamic environments, and its evaluation results may not accurately reflect the complexities encountered in real-world usage. (3) Weight Allocation Issues in Group Decision-Making: In multiple-attribute group decision-making problems, the opinions of different decision-makers may carry different weights. This paper does not thoroughly explore the weight allocation among different decision-makers, which could lead to certain opinions being over- or under-represented, thereby affecting the fairness and reliability of the decision-making process.

In future research, addressing the deficiencies, the following directions can be explored to enhance the comprehensiveness and applicability of the MPPT controller quality evaluation method, and to provide more practical solutions for optimizing photovoltaic systems. (1) Expanding the Range of Parameter Sensitivity Analysis: The current sensitivity analysis is limited in terms of parameter range. Future research could expand the analysis beyond the [1, 5] interval to encompass a broader set of parameter configurations. This would facilitate a deeper understanding of how parameter variations affect overall model performance. Additionally, incorporating simulation tests under various environmental conditions could provide a more comprehensive evaluation of the adaptability and robustness of the SVNN-Com-ExpTODIM method in complex scenarios. Such an expansion would offer stronger support for the model's reliability in real-world applications. (2) Introducing Dynamic Environmental Modeling: To better reflect the complex environmental changes that photovoltaic systems face during actual operation, future research could consider incorporating dynamic environmental modeling into the evaluation framework. For instance, by introducing time series analysis or dynamic simulation tools, it would be possible to simulate the performance of photovoltaic systems under varying conditions such as different sunlight intensities and temperatures. This dynamic modeling would allow the SVNN-Com-ExpTODIM method to more accurately assess MPPT controller performance in fluctuating environments, thereby enhancing its practical value in real-world scenarios. (3) Optimizing Weight Allocation Mechanisms: In MAGDM, the opinions of different decision-makers may carry different levels of importance. Future research could explore more flexible weight allocation mechanisms to optimize the decision-making process. For example, using entropy weighting, fuzzy set theory, or preference-based dynamic weight allocation methods could provide a more reasonable reflection of the influence of different decision-makers. This would ensure the fairness and rationality of group decisions, further improving the applicability and effectiveness of the SVNN-Com-ExpTODIM method in group decision-making contexts.

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