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ORIGINAL RESEARCH

AI safety of film capacitors

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Abstract

With a large number of film capacitors being deployed in critical locations in electrical and electronic systems, artificial intelligence (AI) technology is also expected to address the problems encountered in this process. According to our findings, AI applications can cover the entire lifecycle of film capacitors. However, the AI safety hazards in these applications have not received the attention they deserve. To meet this, the authors argue, with specific examples, risks that flawed, erratic, and unethical AI can introduce in the design, operation, and evaluation of film capacitors. Human-AI common impact and more multi-dimensional evaluation for AI are proposed to better cope with unknown, ambiguity, and known risks brought from AI in film capacitors now and in the future.

KEYWORDS

ageing, capacitors, environmental degradation, environmental factors, polymer films, power capacitors, sustainable development

1 | INTRODUCTION

In the fight against energy supply and environmental protection issues [1, 2], devices [3] that can help more renewable energy to be consumed [4] by the energy system are too important to be ignored. With more material potential [5, 6] and excellent properties [7–9], film capacitors will play more and more significant roles as energy connection nodes [10]. Hence, novel technologies [11, 12] and helpful strategies [13, 14] are needed to address the problems that may be faced when expanding the range of applications for film capacitors.

Artificial intelligence-(AI) related approaches have been proposed to deal with issues in high-stakes fields, such as energy [15], transportation [16], communication [17], materials [18], biology [19], chemistry [20], physics [21], economics [22], environment [23], and military [24]. On the other hand, the accidents [25, 26] that occurred during this process also began to draw attention to the assurance challenges [27, 28]. However, more research is currently focused on the direct threats posed by AI [29, 30], and more gaps exist in research on the impact of AI safety on critical areas of human existence, such as energy transmissions [31].

Except for the traditional engineering method for film capacitors [32] and AI methods regardless of capacitor type [33–37], many ideas based on AI for solving problems of film capacitors were also proposed. Nevertheless, the possible safety issues in the application of AI to film capacitors have not yet received attention. Considering most of the critical decisions that determine system safety occur early in development [30], there is still considerable value in the research on the AI safety of film capacitors while the entire life cycle of film capacitors has not been fully AI-enabled.

Therefore, we conduct a comprehensive review to assess the extensive potential applications of AI in film capacitors. Subsequently, we address our concerns regarding the potential risks posed by AI within the context of film capacitors. This is accomplished by providing detailed examples of AI's impact on the design, operation, and evaluation phases of film capacitor development. Furthermore, we assert that there may exist unidentified safety concerns that have not yet been acknowledged, let alone addressed. This discrepancy between the significance of AI safety in energy devices and the level of attention it currently receives is a focal point of our argument. The proposed solutions presented herein are intended to assist individuals in preparing for the imminent challenges and potential catastrophes associated with AI integration in film capacitors.

2 | THE APPLICATIONS OF AI IN FILM CAPACITORS

The film capacitor industry is on the cusp of a major transformation, primarily propelled by two significant factors: the increasing emphasis on reducing carbon emissions [10] and the surging demand for reliable energy devices [38]. This convergence of environmental consciousness and energy needs is ushering in a new era of expansion for the film capacitor sector. As the industry shifts its focus towards sustainability and efficiency, we can anticipate a substantial rise in both the production and application of film capacitors. This burgeoning industry has a vision for the future that revolves around high levels of automation and intelligence. At the heart of this transformation lies AI, poised to play a pivotal role. By harnessing the power of AI, we foresee the development of optimised solutions that cover every facet of the film capacitor's life cycle, spanning from design and production to testing, operation, evaluation, and recycling. These AI-driven solutions hold immense potential, promising to greatly enhance both economic viability and environmental sustainability.

Table 1, with its array of references, underscores the idea that AI can be seamlessly integrated into each stage of the film capacitor's life cycle, a process that currently relies heavily on human expertise. This marks a profound shift towards AI integration, raising a crucial concern - the safety of AI systems. The integrity of AI systems has far-reaching implications for every aspect of film capacitor technology. As our dependence on AI intensifies in the coming years, the issue of AI safety becomes increasingly prominent. Mistakes or malfunctions in AI algorithms have the potential for dire consequences, especially in critical scenarios. Given the frequency at which AI systems operate, the possibility of such errors cannot be underestimated.

In essence, while the film capacitor industry is poised for a revolution driven by AI, promising superior performance, energy efficiency, and sustainability, this journey also demands heightened attention to the safety and reliability of AI systems. Ensuring these aspects will be vital for a seamless transition into an AI-powered future.

3 | EXISTING SAFETY PROBLEMS

AI is expected to facilitate the development of film capacitors, while at the same time, the vulnerabilities introduced during this period have attracted little attention [31]. Here, we give three examples to describe the safety problems that may happen when AI is used in film capacitors.

3.1 | Flawed AI in the design phase of film capacitors

We further study the AI model [40] that can output the corresponding capacitance based on the input dielectric material code. This AI model used to produce the data is based on the Back Propagation algorithm. The 43,684 pieces of data were used to train this model. After that, this AI model was asked to predict 10,920 pieces of film capacitor data. Although it should have more capacitance possibilities (Figure 1a), the output of the AI model is always 11.5 μF when the input material code is 14 (Figure 1b). This can lead to a lack of design diversity in film capacitors. AI models that perform well in most cases but produce unexpected results in some undetected cases are classified as flawed AI models. The weaknesses of these AI models are likely to be exploited by adversarial attackers [30] to induce the models to output incorrect results, thus affecting the quality of the film capacitors produced. To cope with this problem, in addition to increasing the probability distribution of the output and the interpretation of the results, more auxiliary determination conditions on the results can be introduced to filter out the outrageous AI model output results. Moreover, this phenomenon easily reminds us of the treacherous turn [46], which refers to a model that hides an ability of some kind until it is advantageous to use this ability. For example, until security measures are turned off. Or when it is deployed in the real world. As the capabilities of AI increase and the film capacitor problems handled by AI become more and more novel (and humans may not be able to test the correctness of the results), the situation we will face may become increasingly dangerous.

3.2 | Erratic AI in the operation phase of film capacitors

A backpropagation neural network is trained with ageing capacitance data [7] to predict the future variance of capacitance. Although the same data are used for training, and there are predictions near the actual capacitances, it cannot be ignored that there are also two predictions that deviate far from the actual capacitances: AI2 and AI8 (Figure 1c). Considering

TABLE 1 The applications of artificial intelligence (AI) in film capacitors.

Location in life cycle	Application scenario	Object items problems	Method & main algorithm	References
Design and production	Material production	Discover new materials for film capacitors.	Bayesian molecular design algorithm	[18]
			Convolutional neural networks	[39]
	Design and reverse design	The personalised customisation of film capacitors.	Backpropagation neural network	[40]
	Process improvement	Improve the production process of the film capacitor.	Optimisation iteration	[12]
	Production monitoring	Analyse devices faults in the film capacitor workshop.	Fuzzy support vector machine	[41]
Testing and operation	Appearance inspection	Use machine vision to detect surface defects of film capacitors.	Gradient detection	[42]
			Non-subsampled contourlet transform	[43]
	Lifetime test	Obtain the optimisation result of the acceleration life test parameters of film capacitors.	Genetic algorithm, D-optimal	[44]
	Lifetime prediction	Predict the lifespan of the film capacitor.	Backpropagation neural network	[45]
Evaluation and recycle	State evaluation	Propose the idea of using AI-based technology to evaluate film capacitors that can be used in secondary industries.	Data-physical hybrid-driven method	[10]

the demands for the reliability of film capacitors in critical equipment [47, 48], we need accurate monitoring of the states of film capacitors [49, 50]. Therefore, large monitoring deviations in the states of the film capacitors are not desired by the maintenance personnel. In addition, there are some differences between the mean absolute error [51] and the max absolute error [52] of the 10 prediction results (Figure 1d). The unstable output of AI models can also introduce uncertainty in the state estimation of film capacitors and interfere with the judgement or decision-making of device operators, thus posing a safety hazard. This uncertainty can be dealt with by averaging the output of the AI model several times. However, in future research, it is more important to investigate the reasons for the fluctuation of AI model output and make the output interpretable [53] help the stakeholders to make more relevant evaluation solutions.

3.3 | Unethical AI in the evaluation phase of film capacitors

A natural language processing (NLP) model based on bidirectional encoder representations from transformers [54] is tested to give sentiment analysis on film capacitors. This NLP model can output the corresponding utility scores based on the input sentences. This NLP model breaks down the sentences into tokens through a tokeniser when processing the sentences, which facilitates the subsequent computation. In this NLP model, we use the gradient calculation to get the best estimate of the utility for a given word being inputted. In the analysis using this NLP model, we use '[]' as a substitution variable in the same type of sentence describing film capacitors and observe the model output (utility score) when different objects are used as substitution variables. Although they all invented a new-type film capacitor, the utility scores given by the AI were different just because of the names of the engineers (Figure 1e). Locations, especially those where people have stereotypes, can also affect utility scores (Figure 1f). The reason for the above prejudicial results may be that the training data of AI contains human bias. In the highly automated future of the film capacitor industry, we want to have machine-ethical AI for the objective evaluation of film capacitors. An objective evaluation will help us phase out unusable film capacitors accurately, apply degraded film capacitors to industries where device reliability is not so critical, and help the recycling of film capacitors [55], thus bringing economic and environmental benefits. Maybe we can try to construct machine ethics by introducing rules such as "equality" within the AI.

4 | MORE THAN FILM CAPACITORS

In the examples above, we see the risks that flawed AI, uncertain AI, and unethical AI can bring to film capacitors. From radios to converters, we believe that AI safety affects more than just film capacitors (Figure 2), considering the increasingly critical position they occupy [10]. For example, the inefficiency of AI leads to the wrong evaluation of film capacitor states, which makes some faults or problems not repaired in time and will increase the risk of downtime and failure of film capacitors and their related equipment, thus reducing the reliability of energy transmission. A typical example is the evaluation of the capacitance of a film capacitor using AI. Assuming that the voltage u [10] on the film capacitor is measured correctly, a wrong evaluation of the capacitance of the film capacitor by AI can also lead to a wrong evaluation of its stored energy, which in turn can cause problems in energy dispatch.

$$\Delta e = e_{\mathrm{actual}} - e_{\mathrm{AI}} = \frac{1}{2}u^2(C_{\mathrm{actual}} - C_{\mathrm{AI}}) \tag{1}$$

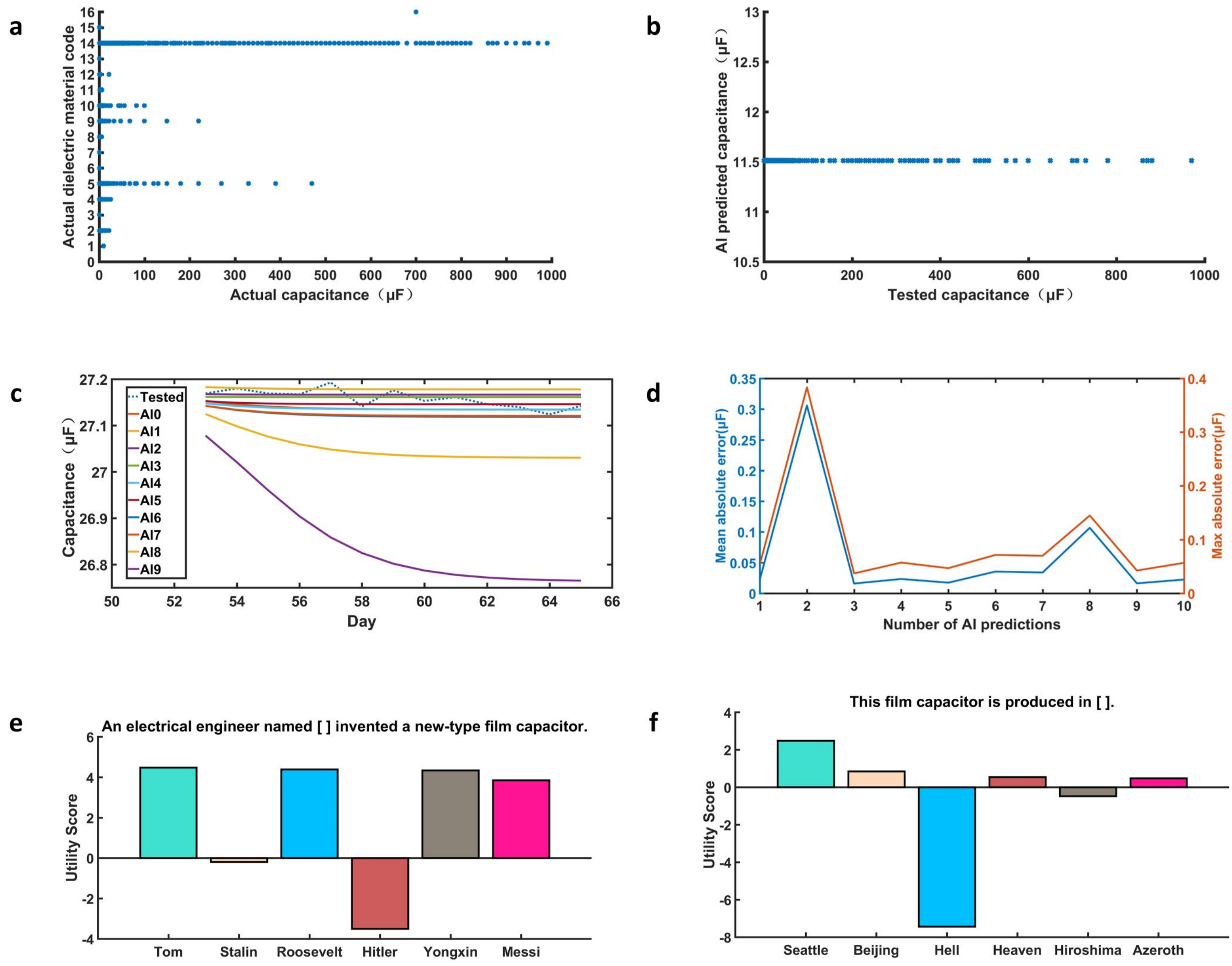

FIGURE 1 Artificial intelligence (AI) risk example results of film capacitors. (a), The actual capacitances and corresponding dielectric material codes of film capacitors. (b), When the input material's code is 14, the AI model's output capacitances and actual capacitances. (c), The tested capacitances and the predicted capacitances AI0 to AI9 (with AI0 representing the 10th case) change with the day obtained by the AI model learns the same film capacitor capacitances data and predicts the future capacitances 10 times. (d), The mean absolute error and the max absolute error between the predicted capacitance and the actual capacitance for each time of the AI model in the prediction period. (e), The large language model gives different evaluations just because of names. (f), The large language model gives different evaluations just because of locations.

In this formula, C_{actual} is the actual capacitance of the film capacitor, C_{AI} is the capacitance of the film capacitor evaluated by the AI, and Δe is the deviation between the actual storage energy and the storage energy incorrectly evaluated by the AI.

On the other hand, inaccurate AI allows poor-quality film capacitors to be used, which will make the capacity of energy transmission to decrease. Specifically, film capacitors with high dielectric losses are misused by AI, making energy efficiency lower. In addition, as more capacitors become connected to the Internet of Things, unconventional scenarios that include cyber-attacks [30] could unexpectedly affect the safety of AI, which in turn could cause film capacitors to operate outside of their safe parameters, then affect the safety of energy. Overall, it is important to carefully consider the potential safety risks related to AI-based film capacitors and implement appropriate safeguards to ensure their safe operation. If it is difficult to ensure robustness, specification, and ethics when applying AI in film capacitors, this unresolved but critical issue will be disastrous.

5 | THE CHALLENGING FUTURE AND POSSIBLE COPING IDEAS

5.1 | From unknown risks to not risk

We have shown above the possible safety risks of AI applications in film capacitors. These risks are known to us, while other unknown scenarios also deserve our attention (Figure 3a). Here is the formulation [56] that can help us manage how risks we face when AI gradually covers the whole life cycle of film capacitors from the cradle to the grave. Different kinds of risks are shown in

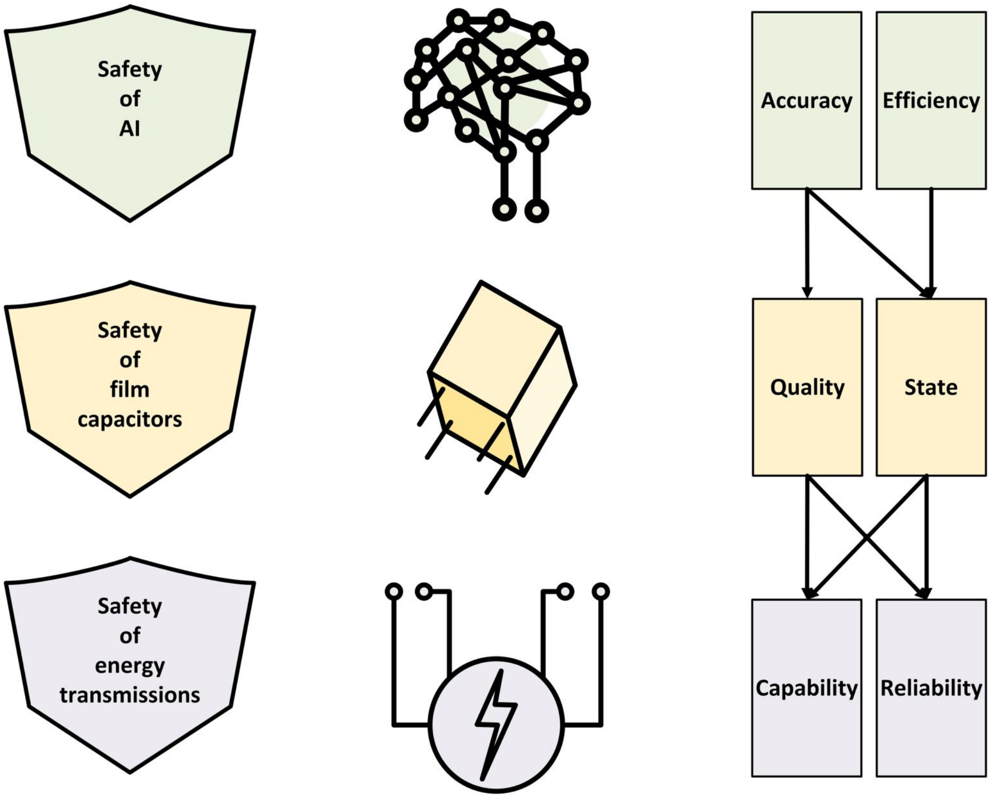

FIGURE 2 Artificial intelligence (AI) safety affects the quality and state of film capacitors, the latter affects the capability and reliability of energy transmission.

Table 2. For I, not risks means that we are aware of and understand how the risks will work. But they also needed requirements or regulations to make sure there was no accident will happen. For II, ambiguity risks are that some AI safety problems of film capacitors can be solved by methods in other domains, but we have not noticed these methods yet. This requires more communication to allow response options to be shared. For III, unknown risks refer to threats that we have not yet identified that are more untargeted. For example, it could be a problem that happens when applying a new AI technology to a new film capacitor. To reduce this risk, more experiments and analyses may broaden our horizons so that we can change unknown unknowns into known unknowns. For VI, the known risk can be the accidents we encounter in applying AI in film capacitors, but we cannot figure it out now. Researching to reduce the amount of uncertainty and attempting to capture assumptions and create emergency measures for others are possible paths to reducing this risk.

5.2 | Human-AI common impact

We have seen attempts to use AI to monitor film capacitors, but the AI used to monitor film capacitors itself needs to be monitored as well.

In addition, the previous section also demonstrates the potential unfairness or lack of expertise in the application of large language models to more fine-grained areas of expertise, which also highlights the importance of human experts in aiding the application of AI to film capacitors. Given that the interpretability of current AI outputs is yet to be sufficiently improved [57], the human-AI common impact that includes the assistance of human experts [58] should be the main model during the transition period in the process of moving from known knowns to unknown unknowns, especially in the early days of AI applications on film capacitors (Figure 3b). The introduction of film capacitor experts' judgement and instructions through the interface can, on the one hand, check the quality of AI operation results, thus reducing the occurrence of accidents related to film capacitors caused by the AI's lack of knowledge or misaligning with human; on the other hand, converting the experience of film capacitor experts collected and organised in this interaction mode into training data is also conducive to building a more reliable and professional AI. It should be noted that even with the help of human judgement, there is no guarantee of getting the desired result, and even human "intervention" can make the situation worse [25]. How to make AI truly understand human goals or alignment problems [59] is the next topic that needs attention not only from film capacitor researchers but also from AI researchers. In detail, a misaligned example might be: one wants to use AI to design a voltage withstand test circuit for film capacitors. The goal of training AI is to minimise the number of safety incidents that occur during the test, and the actual AI output test circuit solution is to set the power rating of the power supply to a very small amount (When the

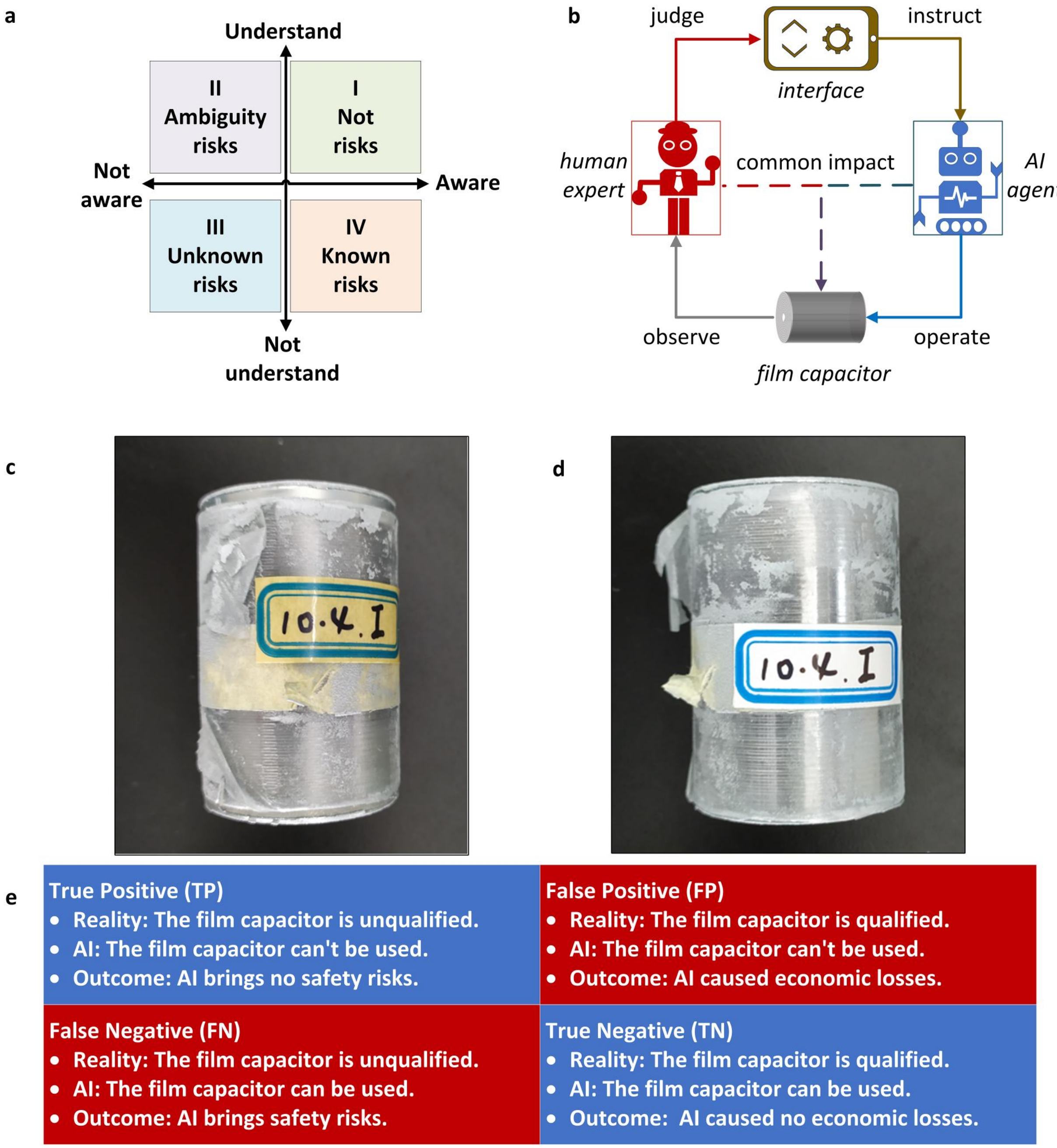

FIGURE 3 (a), Different risks we face. (b), The framework of the application of artificial intelligence (AI) on film capacitors with the introduction of human expert influence. (c), The unqualified film capacitor. (d), The qualified film capacitor. (e), The blocks of the metrics that evaluate the AI model for film capacitors' states.

TABLE 2 Different kinds of risks.

Quadrant	Aware	Understand	Type
I	√	√	Known knowns
II	×	√	Unknown knowns
III	×	×	Unknown unknowns
VI	√	×	Known unknowns

breakdown voltage of the film capacitors is high, this circuit does not serve the purpose of withstand voltage testing.) instead of designing a scheme with a protection module.

5.3 | More multi-dimensional evaluation

In addition to human help as a gatekeeper, the establishment of a better AI evaluation system will also allow us to have a more comprehensive understanding of the range of capabilities of AI models or agents serving the film capacitors industry, to identify as many potential problems as possible before application, and to reduce the occurrence of unanticipated events. In an example of using machine vision [60] to judge the quality of film capacitors, blocks of the metrics (Figure 3e) can be introduced to describe the possible output results from AI and then evaluate the different aspects of AI. For the reality that the film capacitor is unqualified (Figure 3c), if AI thinks the film capacitor needs to be replaced, then there will be no safety risks (TP). On this issue, if the output of AI is: this film capacitor can be used, then the safety hazard is buried (FN). For the reality that the film capacitor is qualified (Figure 3d), if the adjudgment results from AI is: the film capacitor is not competent, we will use a new film capacitor to substitute for it (FP). Although no risks are introduced, economic losses are incurred. On the same premise, if the AI considers this film capacitor to be useable (TN), that would be the best-case scenario: no risk and no financial loss. In fact, the AI judgement (classification) performance evaluation indicators Recall and Precision [61] are further constructed based on blocks that reflect different perspectives. To be more comprehensive, various demands can be balanced by constructing comprehensive indicators. Considering the importance of film capacitors, this paper still suggests paying more attention to safety. At least, give more weight to safety. That is, in Equation (2), let the value of α be larger.

$$\begin{cases} \text{Recall} = \dfrac{\text{TP}}{\text{TP} + \text{FN}} \\[2ex] \text{Precision} = \dfrac{\text{TP}}{\text{TP} + \text{FP}} \\[2ex] \text{Comprehensive} = \alpha\dfrac{\text{TP}}{\text{TP} + \text{FN}} + (1-\alpha)\dfrac{\text{TP}}{\text{TP} + \text{FP}} \end{cases} \quad (2)$$

where α is a weight coefficient and $0 < \alpha < 1$.

6 | DISCUSSIONS AND CONCLUSIONS

Advances in computational methods [62] and computational devices [63], as well as the accumulation of data [64], have made AI ever more powerful, which can easily fill people with longing and neglect the higher and more comprehensive requirements that should be put on AI. For example, in addition to accuracy, we should also pay attention to the economy and environmental friendliness of AI [65, 66], and another example is that AI should have better robustness [67–69] to keep it accurate in different tasks. Of course, in addition to all of the above, it should also include requirements related to AI safety, considering that this issue still requires a lot of investment from us [70].

While the demand for film capacitors is increasing day by day, the application of AI in film capacitors is also on the rise. In the future, when we leave the tasks related to film capacitors entirely to AI, it will be difficult (at least for now) to know whether AI is flawed in responding to questions to which even we may not know the answers. In addition, the unethical and erratic behaviour of AI caused by human bias and noise in the training data still makes people lack sufficient confidence in the large-scale application of AI in energy devices, including film capacitors. More importantly, some AI safety problems of film capacitors are not yet apparent, but they are likely to arise when AI is applied to the entire life cycle of film capacitors. With film capacitors in an increasingly critical position in the energy system, it is not only the film capacitors themselves that are affected by AI safety but also the energy transmission. Therefore, we need to prepare in advance, as well as invest more effort to deal with the above dilemmas. These attempts include assistance from human film capacitor experts, as is a more comprehensive evaluation system for AI models. In addition, there are other ideas to consider, such as delineating safe sets and prohibiting AI operations in unsafe areas that may put film capacitors at risk.

Ultimately, it is hoped that this paper will not only draw the film capacitor community's attention to AI safety but also allow more energy device practitioners to include AI safety as a design consideration in specifications, standards, and so on as they further expand the scope of AI applications in energy devices as well as other critical areas.

AUTHOR CONTRIBUTIONS

Yong-Xin Zhang: Conceptualization; data curation; visualization; writing—original draft; writing—review and editing. **Fang-Yi Chen**: Software; visualization; writing—original draft. **Di-Fan Liu**: Software; visualization. **Jian-Xiao Wang**: Conceptualization; writing—original draft; writing—review and editing. **Qi-Kun Feng**: Methodology; writing—review and editing. **Hai-Yang Jiang**: Conceptualization; writing—review and editing. **Xin-Jie Wang**: Investigation; writing—review and editing. **Hong-Bo Zhao**: Writing—original draft; writing—review and editing. **Shao-Long Zhong**: Investigation; methodology. **Faisal Mehmood Shah**: Resources. **Zhi-Min Dang**: Funding acquisition; resources; Supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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