APPLICATION OF ARTIFICIAL INTELLIGENCE IN PV SYSTEM DESIGN AND OPERATION : A REVIEW

I Wayan Krisnayudi

(07/06/2023)

1 TABLE OF CONTENTS

2 INTRODUCTION

The field of solar energy has experienced significant advancements in recent years, with an emphasis on optimizing the design and performance of photovoltaic (PV) systems. As the demand grows, researchers and engineers are exploring innovative technologies to enhance the efficiency, reliability, and cost-effectiveness of PV installations. Artificial Intelligence (AI) is one such promising technology in this regard.

In this article, we explore the application of AI in PV system design and operation and how it is revolutionizing the way solar energy solutions are developed. By harnessing the power of AI algorithms, data analytics, and machine learning, PV system designers can streamline and improve the design process. Specifically, we will focus on how AI can assist in system layout, material selection, sizing and management energy storage, energy optimization in MPPT technology, and defect detection.

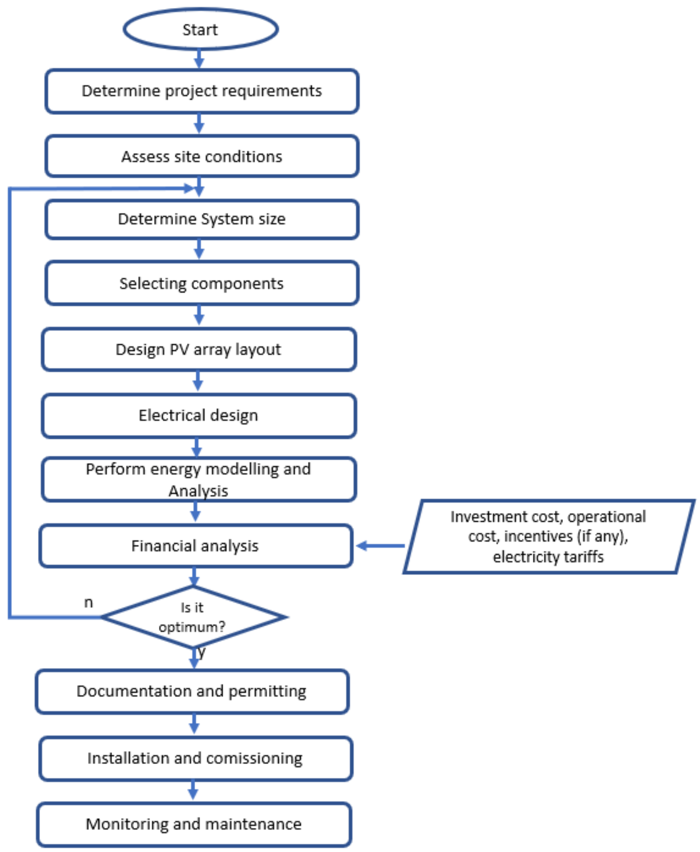

Figure 1. Flow chart of PV System Design and Operation

3 SYSTEM LAYOUT

Optimizing PV system layout is not the trivial solutions. Variables such as the number of panels, space constrain, tilt angle, pitch, PV panel cost, and many other parameters can significantly affect the production and profitability of solar farm.

For example, consider designing an industrial-sized ground-mounted PV farm within limited space. What would be the optimal layout? Should all the panels be placed horizontally without any gaps to maximize the number of panels installed? While this may increase the overall quantity, the efficiency of each panel might be lower. Alternatively, is it better to place the panels with an optimized pitch angle while maintaining proper spacing between rows? This approach may result in higher efficiency per panel, but fewer panels installed. Perhaps the ideal solution lies somewhere between these two extremes, finding a balance between panel quantity and efficiency.

To determine the optimal solution, multiple calculations must be conducted. Certain PV design software, such as PVsyst, offer simulation models known as "optimization tool" and "batch simulation." These models enable users to vary input parameters, iterate through different scenarios, and monitor various output parameters. This valuable feature assists designers in selecting the most suitable values for specific parameters and achieving an optimized solution.

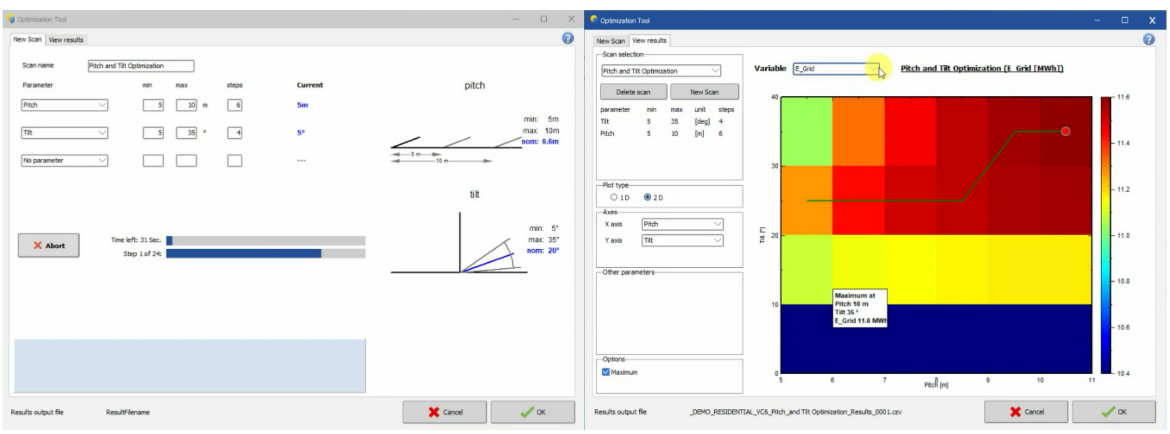

Figure 2. Example of Pitch and Tilt optimization by PVSyst - Optimization tool

However, it is important to acknowledge that this feature in PVsyst does have certain limitations. Firstly, it offers limited optimization options and does not provide optimization for more advanced design parameters, such as module placement. This means that certain aspects of the system may not be fully optimized.

Secondly, the iterative optimization process can be time-consuming, particularly for complex systems or large parameter ranges. The need for multiple iterations can slow down the design process, especially when dealing with extensive setups.

Furthermore, the accuracy of the results heavily relies on the assumption and input provided by the user. If the input data is inaccurate or incomplete, the outcomes may not accurately reflect the real-world performance of the PV system.

Lastly, utilizing this feature effectively requires a certain level of user expertise. Designers must possess a solid understanding of PV system design principles to define the optimization parameters, ranges, and constraints. Without this expertise, setting up meaningful and effective optimization scenarios can be difficult.

AI can help to improve the optimization process of PV system design software, including PVsyst, by employing advanced optimization algorithms and adaptive learning to be able to handle a broader range of parameters and be more efficient over time. Moreover, with the integration of big data, it can also avoid inaccuracy of the user input parameter.

4 COMPONENTS SELECTION

The installation of PV farm involves numerous components, each with various models from different manufacturers. These components have different specifications, prices, and availability, making the task of choosing the right ones overwhelming.

When choosing components for PV systems, the designer typically rely on the experience and expertise based on manufacture reputation, past performance and familiarity. However, this is not ideal due to the fast-paced technology advancements and the large market with many manufacturers offering various products. To make better component choices, it is better to use data-driven decision based on factors like performance, cost, reliability, and other relevant considerations.

Some PV system design software, for instance PVSyst, have the components library that contains pre-defined models and specification of various components used in PV system design such as PV modules, inverters, batteries and other relevant components. The purpose is to provide user with a comprehensive resource that they can choose from when designing the PV System. However it may not be sufficient, because it still require a significant amount of time to search and select most suitable components.

AI can indeed play an important role here. By accessing and analyzing library and database of every components, AI can efficiently evaluate component specifications, performance data, pricing, and other relevant factors, to assist in material selection. This not only saves time but also helps designers make better material selections

5 SIZING AND MANAGEMENT OF ENERGY STORAGE

Like any other renewable energy plants, PV plants are dependent on the availability of its natural resource, which is sunlight, and therefore conditioned by their intermittency. In addition to intermittency, the production curve of PV often cannot match the demand curve. The PV can only produce the electricity during the day, but for some cases, like the residential application, the demand is even higher in the evening.

Installing an energy storage system can help mitigate intermittency and bridge the gap between energy generation and demand. Furthermore, it can be beneficial in capturing surplus energy during times of high production and low demand, storing it for use when production is low and demand is high due to fluctuating electricity tariffs.

Two challenges arise in the field of energy storage. One is developing method of managing the charging and discharging of the storage system. The other is the correct sizing of the installation.

5.1 ENERGY STORAGE MANAGEMENT

Artificial intelligence (AI) can come into play to give huge improvement to the management of energy storage solutions. The improvements can include:

- Optimization of their operations by controlling when they are charged and discharged depending on the electricity price,
- Controlling how and when they are charged every day to achieve a longer cycle life,
- coordinating their operations with other energy storage solutions, power generation capacities, and consumers,
- predicting when a failure will occur and act before it happens. For example, if a lithium-ion storage system suffers a thermal runaway or other degradation-inducing event, the batteries will not recover, and the system may become a permanently low-performing or even stranded asset

A case study of microgrid in the state of Western Australia showed that the intelligence added to the Battery Energy Storage System (BESS) control could achieve 6.5%, 7.6% and 11.5% reduction of the annual generation cost and 2.8, 2.7 and 2.7 years shorter payback time in the Islanded, Grid-connected with no-export and Grid-connected with export operating modes respectively [1].

5.2 ENERGY STORAGE SIZING

Properly sizing energy storage in a PV system is crucial because it ensures that the storage capacity matches the system's requirements. A well-sized energy storage system can provide reliable backup power, optimize energy utilization, and effectively balance supply and demand. It allows for efficient load management, maximizes self-consumption of solar energy, and enhances the integration of renewable resources. By accurately sizing the energy storage, system performance is optimized, energy costs are reduced, and overall system resilience and reliability are improved.

AI can be valuable in the optimization of storage sizing. Through advanced algorithms and machine learning techniques, AI can analyze data on energy consumption patterns, solar generation profiles, and other relevant factors to provide optimized storage capacity recommendations. Moreover, AI can handle complex calculations and simulations, considering various parameters and constraints, leading to more precise and efficient sizing decisions. Figure below show the detailed sizing process, which includes self-adaptation and monitoring for the dispatch rules of BESS

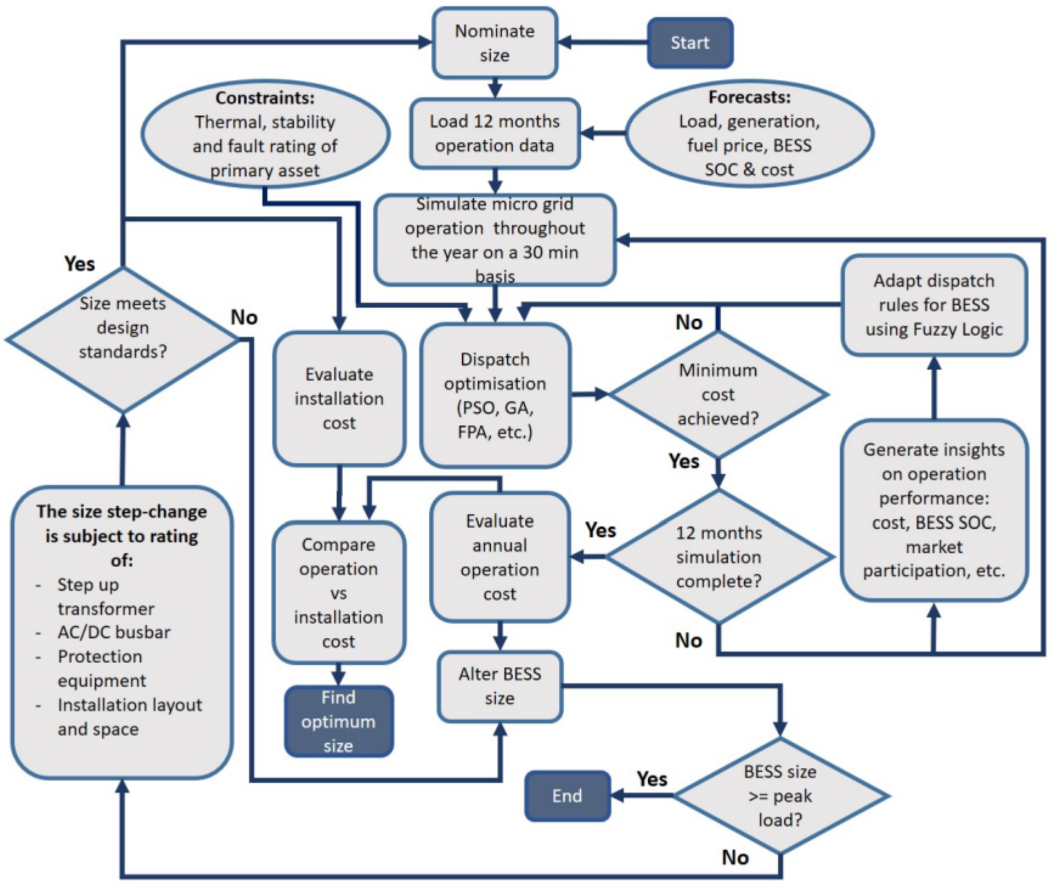

Figure 3. Battery Energy Storage System (BEES) optimal sizing process

6 ENERGY OPTIMIZATION IN MPPT TECHNOLOGY

One of the important problem in PV installation is related to optimizing energy production. PV cells have a complex relationship between their environment and power they can produce. Along the I-V curve (Figure 4) of solar cells, there is a point where the power will be maximized, this is called the maximum power point. The I-V curves and the MPP point usually changes over time depending on conditions such as irradiation, temperature, the state of the PV cells, and shading condition. Moreover, the I-V curves are usually taken not from single PV cell, but from one single module or even from a PV array, that makes the IV curve more complex and makes the MPP is harder to be tracked.

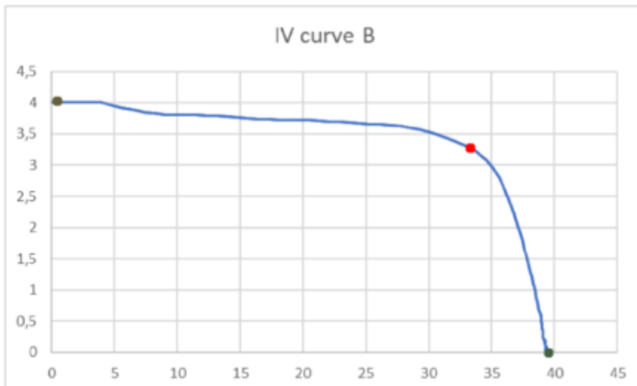

Figure 4. Example of I-V curves of PV panel

The tracking of the maximum power point has been considered in numerous ways, from traditional and simple methods to methods that use complex technology. Recent trends show that AI MPPT techniques, such as, artificial neural network, (ANN), particle swarm optimization (PSO), Ant colony optimization (ACO), genetic algorithm (GA) are also implemented to solve this problem. These techniques are able to track MPP in different environment and partial shade condition. Besides, AI-MPPT can track MPP quicker because by learning from the past experiences, they can start tracking from the last MPP. The main drawbacks of AI-MPPT techniques are highly demanding in term of computational cost and require a large amount of data. However this is not as important as it used to be thanks to the higher performance computer and high availability of data.

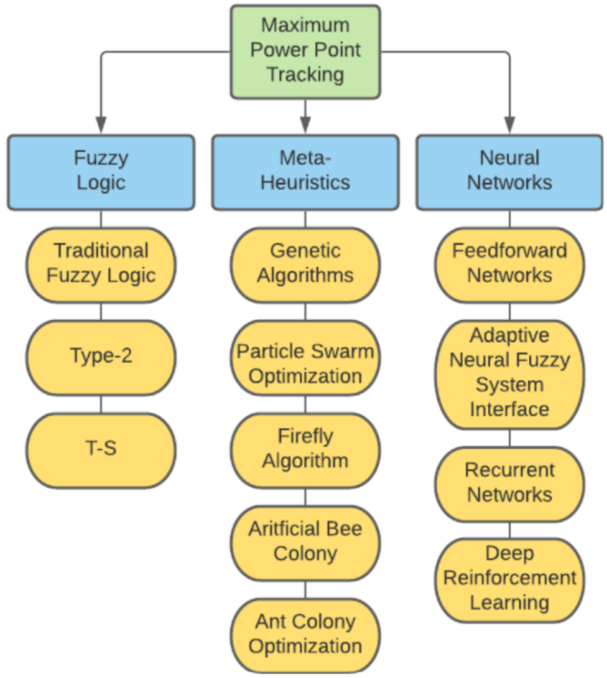

Figure 5. Taxonomy of most used AI method for MPPT

7 DEFECT DETECTION

The defect in PV panel affects the production of the module, making it not work at all in the worst case. The traditional way of finding defect is by performing a manual visual inspection, but it leads to slow detection speed, and the accuracy is affected by personal subjective judgement. Besides, the size of the solar farms has made this method almost unmanageable. In order to solve this problem, different techniques have been proposed, most of them using electroluminescence (EL). The EL images can directly reflect internal defects that cannot be recognized by the human eye, such as hidden cracks, virtual wedding, black spots, etc.

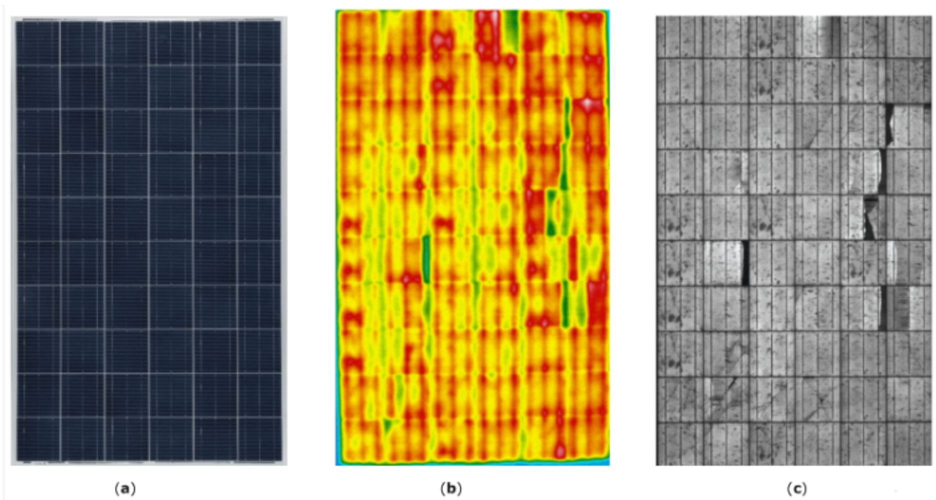

Figure 6. Different techniques for photography modules. (a) Visual spectrum; (b) thermography; (c) electroluminescence

In some studies, a defect detection method of photovoltaic modules based on deep learning is proposed. This method first obtains the mapping relationship between training samples and defect free templates by learning a large number of defect samples. The defect detection of samples is realized by comparing the reconstructed image with the defect image.

In conclusion, the deep learning method can effectively solve the defect detection problem of the EL image of the solar module. A model, like convolutional neural network aided by a complementary Attention network, was reported to even reach 99,17% of accuracy [2]. However, in practical applications, deep learning method still has some shortcomings because it takes a long time, which poses a challenge to image processing at high pixel level.

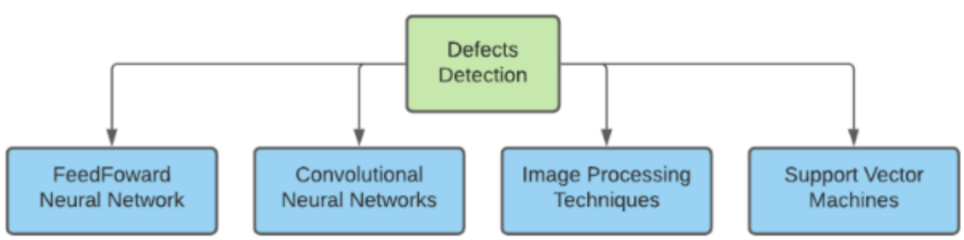

Figure 7. Most used IA method for defect detection

Type	Features	Accuracy	Dataset Size
Image Processing Techniques	Segmentation + obtention of binary image + classification. [128]	from 80% to 99%	—
SVM + Image Processing Techniques	Images are preprocessed and features are extracted from the image. These features are used in an SVM with penalty parameter weighting. [129]	97%	13,392
SVM and CNN	Pretrained VGG19 using different feature descriptors. Similar results for both methods. [130]	82.4%	2624
	CNN is composed of 2 layers using leaky-relu. SVM trained with different features extracted from the images. Similar behavior in both models. [131]	98%	540
	CNN is composed of 2 convolutional layers. SVM parameters optimized by search grid. [133]	96%.	2840
CNN	Thirteen convolutional layers, an adaptation of VGG16. Uses oversampling and data augmentation. [132]	Uses a different measurement	5400
	Multichannel CNN. Accepts inputs of different sizes. Improves the feature extraction of single-channel CNN. [134]	96.76%	8301
	Six convolutional layers. Regulation techniques such as batch optimization. [135]	93%	2624
	Fully Convolutional Neural Network. Pretrained u-net, composed of 21 convolutional layers. [136]	Uses a different measurement	542
	CNN aided by a Complementary Attention Network, composed of a channel-wise attention subnetwork connected with a spatial attention subnetwork. Usable with different CNNs. [138]	99.17%	2300
WT+ SVM and FFNN	Combines discrete WT and stationary WT to extract features and SVM and FFNN to classify them. [137]	93.6%	2029
CNN + SVM, KNN, etc.	Extracts features from different networks, combining them with minimum redundancy and maximum relevance for feature selection. Uses Resnet-50, VGG-16, VGG-19 and DarkNet-19. [140]	94.52%	2624

Figure 8. Summary of the revied models for defect detection

8 Conclusion

In conclusion, the application of Artificial Intelligence (AI) in PV system design and operation has emerged as a game-changer. AI shows a tremendous potential in various aspects, including optimization system layout, material selection, energy storage sizing and management, MPPT technology and defect detection. As AI continues to advance, it will unlock new opportunities for improving the efficiency, reliability, and cost-effectiveness of PV systems. The integration of AI in PV system design marks a promising step towards a more sustainable and technologically advanced future in solar energy sector.

9 References

[1] B. A. M. Y. H. T.S. Mahmoud, "The Role of Intelligent Generation Control Algorithms in Finding Optimum Size for Battery Energy Storage Systems (BESS) in microgrids: A Case Study from Western Australia," *Elsevier Energy Conversion and Management,* 2019.

[2] M. R. H. Romero, "Applications of Artificial Intelligence to Photovoltaic Systems : A Review," *MDPI Applied Sciences Journal,* 2022.

[3] R. G. a. R. P. H. Patel, "Artificial intelligence based MPPT techniques for Solar PV System: A Review," *Journal of Emerging Technologies and Innovative Research,* 2019.

[4] P. Z. a. Q. L. B. Ni, "Intelligent Defect Detection Method of Photovoltaic Modules Based on Deep Learning," in *International Conference on Transportation & Logistics, Information & Communication, Smart City*, 2018.

[5] L. G. J. C. a. E. G. C. Garcia-Santacruz, "Sizing and Management of Energy Storage Systems in Large-Scale Power Plants Using Price Control and Artificial Intelligence," *MDPI Energies Journal,* 2021.