Digital Twin based Maximum Power Point Estimation for Photovoltaic Systems

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***Abstract*—Optimizing the output power of photovoltaic (PV) systems requires quantitative information on the global maximum power point (GMPP). The conventional maximum power point tracking (MPPT) algorithms cannot ensure the GMPP is obtained. This research developed a digital twin-based technique to estimate the GMPP. The PV system built in the simulation environment is transferred to the complex real-world while improving the accuracy and robustness of the algorithm in the real-world environment. The experimental results show that the suggested technique can bridge the gap between conventional models and real-world PV systems.**

***Index Terms*—digital twin, transfer learning, photovoltaic systems, maximum power point estimation**

I. Introduction

In the last decade, tremendous attention and considerable investments have focused on photovoltaic (PV) systems. As a renewable energy source, PV systems play an essential role in reducing the greenhouse effect, coping with the depletion of primary energy sources, responding to energy demand, etc. However, the non-linearity of the PV system and the influence of environmental factors bring significant challenges to its power optimization.

Several research efforts have attempted to describe the output characteristics of PV systems. Kermadi et al. [1] proposed a generalized analytical approach to model the PV arrays under partial shading conditions (PSC). It requires the PV modules' standard test conditions (STC) and the irradiance level imposed on each module. Pendem et al. [2] analyzed and compared different PV array configurations under PSCs. In their work, the smallest unit of analysis is the PV module. A cell-level PV string model was proposed by Ma et al. [3]. The shading information matrix, including critical environmental factors for operation locations, is used to describe the observed current-voltage (I–V) data. However, it is difficult to accurately understand the solar irradiance and temperature of each PV cell in the real world. The same problem also appears in commercial simulation software such as Simulink and PSIM. Currently, no algorithm can accurately identify the complex shading conditions in nature and the resulting changes in PV system output characteristics.

The aforementioned research void is defined as the simulation to real-world (sim-to-real) gap in the PV system in this paper. Undoubtedly, the sim-to-real gap brings challenges to the practical application of the MPPE algorithm. If an analytical model or a machine learning model mainly established by simulation data is applied in a real-world environment, the discrepancy between the real-world and simulation environment will bring about a decrease in the performance or even invalidity in the strategy. For example, a performance drop of up to 20% for R-squared value was reported in [4] for the artificial neural network (ANN) based MPPE model [5]. In [3], a relative error of 0.235 under specific scenarios is reported.

In a PV system, discrepancies in the physical characteristics of the PV strings are the primary cause of the sim-to-real gap. Furthermore, these PV string properties may fluctuate dramatically owing to temperature, humidity, location, or wear-and-tear over time. The traditional idea is to incorporate these influences into the MPPE process as much as possible. However, this will significantly increase the computational cost and the difficulty of the model. In contrast, we build a digital twin model for the PV system, eliminating the error between the real-world and simulation environment through an artificial neural network. Real-world tests also demonstrate that the suggested strategy may effectively bridge the sim-to-real gap.

II. Methodology

In this section, a shading matrix construction based on feature point extraction is used to analytically describe the output characteristics of the PV string. Furthermore, the error of the analytical model and the real-world is eliminated by the digital twin model.

A. Digital Twin Model

Fig. 1 shows the system topology of the digital twin model. We first construct the x_{real} database by collecting the shading matrix of the real-world PV systems. The shading matrix is defined as a vectorized description of the shading condition of a PV string according to [4]. The position of the global

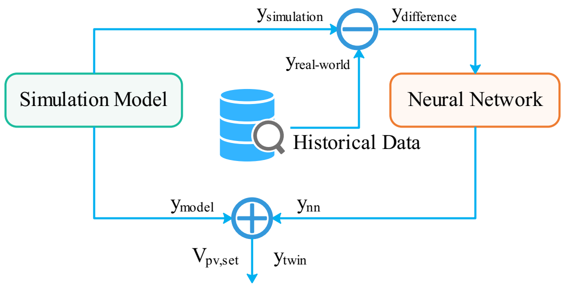

Fig. 1. Schematic diagram of the proposed MPPE system.

maximum power point (GMPP) can be extrapolated from the shading matrix. At the same time, we construct an analytical model of these PV systems in the digital space, and an x_{model} database is generated [6]. There is a deviation between the inference results from x_{real} and x_{model} due to the sim-to-real gap. Therefore, we model the gap through a neural network. In the MPPE process, we map x_{real} to x_{model}, and the output is added with the deviations from the neural network to obtain the results of the MPPE.

III. Simulations

TABLE I
SPECIFICATIONS OF THE PV MODULE UNDER STANDARD TEST CONDITIONS

Parameter	Value
Maximum Power P_{mpp}	50.00W
Open Circuit Voltage V_{oc}	22.02V
Short Circuit Current I_{sc}	3.18A
Voltage at P_{mpp}	17.82V
Current at P_{mpp}	2.80A
Cells per Module	36

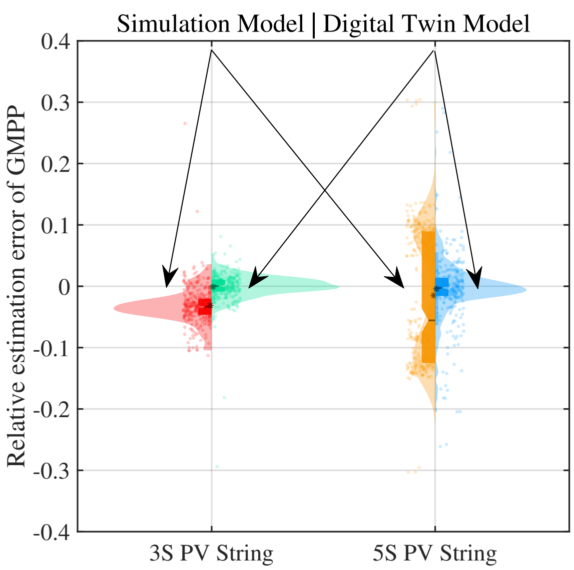

Fig. 2. GMPP error distributions of the simulation model and the proposed digital twin model.

The proposed MPPE approach is simulated and evaluated using MATLAB/Simulink with the PV modules whose specifications are listed in Table. I. PV strings with three and five PV modules in series connection were used to collect samples under various atmospheric conditions. A PROVA PV system analyzer was used to capture I-V data and atmospheric information. This data collection covers the real-time characteristics of a PV string over five days. Fig. 2 shows the error distribution of MPPE results of the proposed method in terms of the GMPP voltage. It can be seen that the proposed method significantly improves the accuracy of the analytical model-based MPPE system. The average relative error of the estimated GMPP between the simulation model and the real world is around 4% and 5%, respectively. With the proposed algorithm, the sim-to-real error is eliminated. The error distributions' median value has been around zero for both 3S and 5S PV strings.

IV. Conclusions

In this paper, a digital twin-based MPPE approach was proposed. We demonstrated the use of digital twin to estimate the GMPP is capable of bridging the sim-to-real gap. The proposed method improved performance of estimation and shows a promising application for GMPPT system.

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