# Digital Twin-Based Approach for Monitoring and Event Detection in PV Systems


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*Abstract*—**In solar power generation, photovoltaic (PV) panels are used to convert solar radiation into electrical energy with the help of different assets. They are prone to a variety of defects as a result of the environment's continual change. These defects should be discovered and remedied as soon as possible so that the PV panels' efficiency and durability are not compromised. Therefore, regular monitoring and accurate diagnosis are challenging and critical for any PV plant for high-efficiency production and improved system performance. To deal with all these challenges, the Digital Twin (DT) technology as an integrated solution to detect and classify faults in the PV system arrays is proposed. The presented method is based on the calculation results of the array currents produced using the DT model and compared with the observed output collected from the physical PV system. In this study, the correlation coefficient $R^2$ was used to evaluate the accuracy of the created twin model and detect different events in the PV arrays. In addition, the three-dimensional DT platform is created, which is composed of the real-time simulation of the physical PV system, the twin model, and the communication link between them. The proposed technique is tested and evaluated under several PV fault scenarios.**



***Keywords— PV System, Digital Twin, Fault Detection and Monitoring.***


## I. Introduction

Renewable energy is a major, difficult issue that is receiving more and more attention globally. With zero CO2 emissions, renewable energy sources like wind and solar are safe, clean, sustainable, and environmentally acceptable substitutes for traditional fossil fuels. Additionally, by lowering a nation's reliance on fossil fuels, solar PV energy—one of the most economically viable and sustainable renewable energy sources—increases that nation's energy security. It is well known that weather resources significantly impact solar and wind energy with intermittent and fluctuating features. Photovoltaic power output is highly erratic and variable due to temperature, sun irradiation, and other random factors; therefore, it is hard to predict photovoltaic power precisely [1].

For PV systems, over the past decade, the global cumulative installed Photovoltaic (PV) systems capacity has grown exponentially. PV deployment will continue to grow as the global energy portfolio transitions towards renewable energy. Due to its low cost relative to other sources, PV's share of the total electricity supply will increase significantly as shown in Fig. 1. However, PV system production (electricity generated) may be impacted by several factors, including solar resources, module age, and different types of events, which result in financial/technical losses. In addition, failing to obtain adequate information when monitoring the PV system can lead to several obstacles such as the difficulty of distinguishing underperformance between PV modules and other components. This can impact the overall system's reliability and survivability. The long-term reliability of PV modules is crucial to ensure PV's technical and economic viability as a successful energy source.

Indeed, a variety of faults and failures, such as short-circuit, open-circuit, and shading faults, can commonly affect PV systems and the power provided by the PV modules. Maintaining a PV system's proper operation and safety while producing the required amount of power in grid-connected PV systems continues to be a significant difficulty [2]. Consequently, safety engineering practitioners and researchers have recently focused especially on PV system monitoring and fault detection schemes. Many fault detection approaches that fall under one of several categories have been developed due to increased focus on fault detection and safety.

Recent research work has tried to tackle these problems. Techniques for detecting PV electrical faults include I-V curve tracing, infrared thermography time-domain reflectometry (TDR), data monitoring and analysis, and impedance spectroscopy. One of the most significant techniques, I-V curve tracing, involves measuring and analyzing the current-voltage characteristics of PV modules, strings, or arrays to detect performance degradation, mismatch losses, and various electrical defects, with automated systems for continuous monitoring and fault detection [3]. Furthermore, thermal imaging techniques can identify hot spots caused by electrical faults such as cell interconnection failures, bypass diode failures, or mismatch conditions [4]. Importantly, TDR is a cable testing technique that can detect open or short circuits in PV strings or arrays by analyzing the reflections of electrical pulses along the conductors [5].


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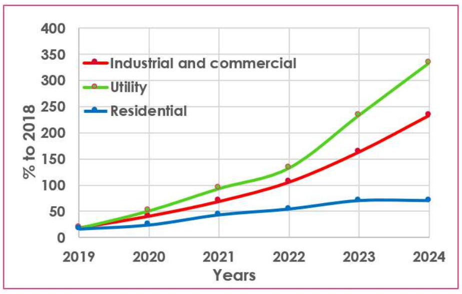


Fig. 1. PV system growth referenced by 2018.

Continuous monitoring of system performance data, such as voltage, current, and power output, can aid in detecting anomalies and identifying potential electrical faults through data analytics and machine learning techniques [6]. Furthermore, impedance spectroscopy is a non-destructive technique that measures the electrical impedance of PV modules or cells at different frequencies, providing insights into various degradation mechanisms and electrical defects [7]. Compared with these solutions, the digital twin model, which is continuously updated and synchronized from sources, provides near real-time status updates, working conditions, and operational challenges playing out in the field. This paper describes the creation of a fault detection and monitoring system that uses the concept of a digital twin to monitor the output currents from photovoltaic (PV) system arrays. Specifically, we generate arrays' current using measured temperature and irradiance using the digital twin model. Then, compare the measured currents from the actual system with the prediction obtained from the digital twin model for monitoring and fault detection.

## II. PV System and Typical Faults

The PV system usually contains the following key physical components: PV arrays, which consist of several module strings, trackers, combiner boxes, inverters, and power transmission links between these components and the grid components, such as power transformers, as shown in Fig. 2. In this system, the modules are arranged in strings and arrays depending on the total power, the technical characteristics of the modules, and the type of inverter used. Solar combiner boxes are used to bring the output of several solar strings together and transfer the output to the inverters. These boxes accommodate current and voltage protection devices, disconnectors, and combiners may be equipped with monitoring devices to measure current, voltage, and temperature to ensure the strings' availability and maximize generation. The inverter and transformers are used to adapt the output power from PV arrays to the power grid based on the grid standards. On the other hand, Photovoltaic (PV) systems are susceptible to various electrical defects that can significantly impact their performance, reliability, and safety. These faults can occur at the module, array, or system levels and can arise from various factors, including manufacturing defects, environmental stresses, and system design flaws. Electrical defects in PV systems can lead to power losses, safety hazards, and even complete system failure if not detected and addressed promptly. Typical electrical faults in PV modules and arrays include cell interconnection, bypass diode, junction box, ground, string, and mismatch failures. Cell interconnection failures, where broken or corroded cell interconnections can lead to open-circuit or high-resistance paths, result in power losses and potential hot spots [8].

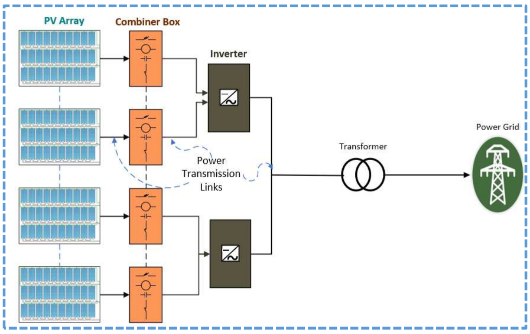


Fig. 2. General PV system components.

Furthermore, loose connections, corrosion, or water ingress in the junction box can cause electrical faults and safety hazards . Open or short circuits in series strings can lead to complete power loss or create potential-induced degradation (PID) conditions [9]. Additionally, electrical mismatches between modules or strings due to manufacturing tolerances or varying environmental conditions can cause power losses and hot spots. Poor connections between PV cells, modules, or arrays can result in increased resistive losses, voltage drops, and uneven power distribution, reducing system performance and reliability [10]. Detecting and addressing electrical defects in PV systems is crucial for maintaining optimal performance, ensuring safety, and prolonging the system's lifespan. Regular inspections, monitoring, and advanced diagnostic techniques play a vital role in identifying and mitigating these defects, ultimately improving the reliability and efficiency of PV installations. With the integration of digital technology and communication infrastructure into various components of the energy systems, significant system operation issues are brought on by the vast volume of generated data, the real-time analysis, and the reaction requirements of the PV system.

## III. Digital Twin in Solar Energy

Professor Grieves introduced the idea of a "digital twin" for the first time in 2003 at a lecture on product life cycle management at the University of Michigan. Subsequently, the US Department of Defense used the idea of digital twins to problems like spacecraft health maintenance. According to NASA, a digital twin is an aircraft or system that is entirely directed toward the goal of mapping the state of its corresponding physical aircraft while utilizing the best available physical models, sensors, and operational history data [11]. It also integrates multidisciplinary and multi-scale probabilistic simulation techniques. It is essential to define Digital Twin because it is the most significant term in our research. The DT is defined as the virtual replicas or models of the physical object/thing with bidirectional real-time data flow between them. This data includes physical measurements, manufacturing data, operational data, and insights from analytics software. A digital twin assists with experimentation and hypothesis testing when adjusting input variables. The basis and center of digital twin theories and technologies is the model. The conventional Grieves three-dimensional digital twin model is made up of three elements: the physical entity in the real space, the twin model in the virtual space, and the communication link, and is distinguished by the physical-virtual interaction as shown in Fig. 3 [12]. In recent years, there has been a rise in investment in solar energy projects as well as an increase in the usage of cutting-edge technologies like edge computing, IoT, and digital twins to optimize solar operations and maintenance. When digital twins are used effectively, solar asset managers can identify early patterns of system underperformance. This information can then be used to forecast future problems and estimate the impact of current

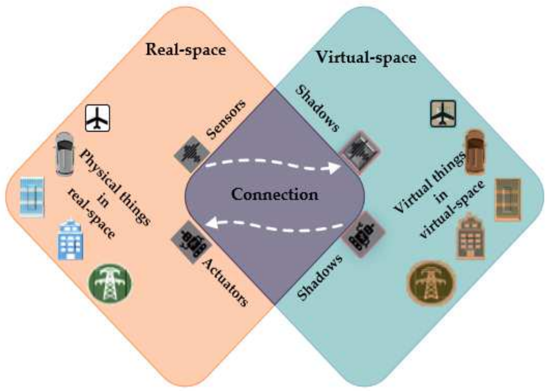


Fig. 3. Digital twin components.

and prospective losses or faults in solar power plants. When digital twins are used effectively, solar asset managers can identify early patterns of system underperformance. This information can then be used to forecast future problems and estimate the impact of current and prospective losses or faults in solar power plants. When closely examining how solar PV cells function under different circumstances, the developed Digital Twin technology is highly successful. Administrators can also test scenarios in the simulated plant and see how the updated panels react. In this approach, the digital twin will not only introduce a virtual replica of the physical assets of the PV system for state estimation and prediction but also will introduce the appropriate scenario of operation during events such as asset loss or asset failure and maintenance to guarantee continued operation. When measured fault condition data are insufficient, the DT-PV system can generate system performance data that is almost accurate, offering exceptional possibilities for event detection. It will also provide appropriate guidelines for optimal operation as well as proper maintenance coinciding with the optimal selected scenario of operation. It also helps with system behavior prediction and life cycle management for solar power plants.

## IV. Studied PV System

The solar cells transform sunlight into DC power. A PV array energy system is formed by connecting several PV modules in series and parallel, each with a different voltage and power capacity. This cluster converts sunlight into electrical power and adapts to variations in temperature and solar radiation. This is often connected to the DC bus and managed by an MPPT-controlled DC-DC boost converter to maximize PV power output and boost the voltage of PV to rated voltage under all operating circumstances. A solar PV array can be modeled using a variety of techniques. The PV array is simulated in this work using a five-parameter model as shown in Fig. 4 [13]. It uses a sun-powered current source connected in parallel to a series resistor, shunt resistor, and a diode that is connected at the output. According to the theory of semiconductors, the V-I characteristics of the ideal PV cell can be described as follows:

$$I = I_{ph,cell} - \underbrace{I_{o,cell}\left[exp\left(\frac{qV}{akT}\right) - 1\right]}_{I_d} \quad (1)$$

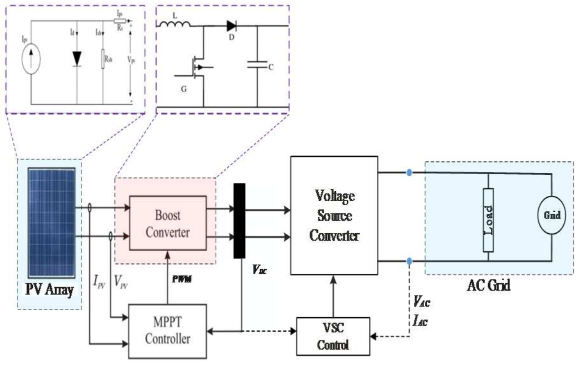


Fig. 4. PV system components

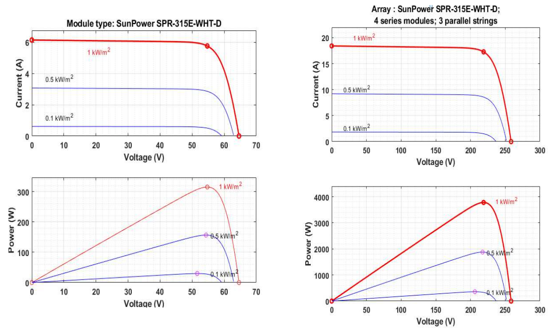


Fig. 5. V-I and P-V curves of the studied PV cell

where, V and I are the module voltage and current respectively, $I_{ph,cell}$ is the generated current from the incident light, $I_d$ is the Shockley diode equation, $I_{o,cell}$ represents the reverse saturation current, the electron charge $q$ is 1.602176468 x$10^{-19}$ C, Boltzmann constant $k$ equal 1.3806503 x$10^{-23}$ J/K, while $a$ and $T$ are the diode ideality constant and temperature in Kelvin, respectively. Practically, the PV module is practically composed of multiple $N_s$ series and $N_p$ parallel cells to provide the required specifications. Hence, the typical PV characteristic equation can be rewritten as:

$$I = I_{pv} - I_o\left[exp\left(\frac{V + R_S I}{V_t\, a}\right) - 1\right] - \frac{V + R_S I}{R_p} \quad (2)$$

$$\text{as,}\begin{cases} I_{pv} = N_p\, I_{pv,cell} \\ I_0 = N_p\, I_{o,cells} \\ V_t = N_s\, \frac{kT}{q} \end{cases} \quad (3)$$

where $I_{pv}$ is the photovoltaic current, $I_o$ is the saturation current, $R_p$ and $R_S$ are the equivalent parallel and series resistances of the array, respectively. These two resistances are mainly replicating the physical characteristics of the PV module. The influence of the $R_S$ appears mainly when the PV acts as voltage source. Therefore, its value usually is very small. In contrast, the $R_p$ normally has a higher value and has a stronger influence at the current source operating mode of the PV system. Hence, Determining the light-generated current $I_{pv}$ of each cell without considering the effects of $R_p$ and $R_s$ poses challenges. Typically, datasheets only provide information on the nominal short-circuit current ( $I_{sc}$ ) representing the maximum current attainable at the device's terminals under standard test conditions (STC) of 25 °C and 1000 W/m$^2$. It is commonly assumed that $I_{sc}$ and $I_{pv}$ are equal in the modeling of PV devices, owing to the low series and high parallel resistance in practical devices. Therefore, the light-generated current of a PV cell varies linearly with solar irradiation and is further influenced by temperature, as expressed by (4):

$$I_A = \left(I_{pv,STC} + \alpha_I \Delta_T\right) \frac{I_r}{I_{rn}} \tag{4}$$

where $I_{pv,STC}$ is the light-generated current at standard test conditions, $\Delta_T$ is the difference between the actual and STC temperatures in Kelvin, $\alpha_I$ does the manufacturer provide the does the manufacturer provide the and represents the temperature coefficient of the short-circuit current (A/K), $I_r$ is the irradiation on the PV surface, and $I_{rn}$ is the STC irradiance. The V-I and P-V curves of the SunPower SPR-315E-WHT-D module and array used in this study are shown in Fig. 5.

## V. Proposed DT Platform for PV System

In this work, we aim to build a DT model for a PV system to deal with events occurring in the PV modules and arrays. Based on the three-dimensional description of the DT concept, a comprehensive modeling and simulation is built and executed on several machines within the ESRL testbed as shown in Fig. 6. The figure depicts the diagram of the digital twin platform developed in this work. As illustrated in the figure, each machine hosts the model of specific dimensions in the system: physical model, communication link, and twin model. In order to enable data connectivity on the system, Ethernet is a popular and easily available data communications technology that supports a wide range of protocols, including TCP/IP and UDP.

### A. Real-time Physical PV System Simulation

In the physical domain, the PV system is modeled using the OPAL-RT (OP4610XG), which provides a complete hardware and software solution, allowing the PV system to operate in real-time. The studied PV system is grid-connected, with almost 19 kW from five arrays. Each array has three parallel strings with each string including four modules connected in series. Each array is connected to a DC combiner box and then to a DC/DC converter. The DC output voltage of the array is set to 500Vdc for the DC/DC converter with a maximum power point tracking (MPPT) controller. All DC/DC converters are connected to an inverter with an AC output phase voltage of 260V.

### B. Data Communication Emulation

In this domain, simulators represent communication processes as the sequential processing and transmission of (virtual) messages and signals using abstractions of the deployed hardware and software. Discrete-event network simulator ns-3 is used to simulate dedicated and all-purpose power communication networks, as shown in the middle of Fig. 6. Utilizing Linux OS to manage the two primary components of the communication network architecture, as demonstrated in [14]: The setup consists of two key components: ns3 for communication network emulation and Docker containers acting as proxies for data flow between the network nodes in ns3 and the OPAL-RT simulation. These containers can be considered as edge nodes for both the physical system and the twin model to enable the exchange of measurement and control signals in both directions. It suggests a simulation approach where any client/server application can run within a Linux container with a variable number of nodes. The communication network in the modular implementation of ns3 is built upon the core library. On top of the ns-3 architecture, a library of network model protocols can be implemented, including multicasting, IP-based applications (TCP, UDP), routing, and wireless and wired networks. The data flow between these containers through the ns3 was implemented and tested in [15].

### C. Digital Twin Model

A digital twin is a quicker method of comparing the actual performance of a photovoltaic plant with its predicted performance derived from its digital duplicate under certain conditions. The Digital Twin's construction from system parameters and enhancement by actual data from the physical system is its primary feature. In addition to real-time plant data, the only inputs required for producing a Digital Twin of a Solar PV plant are temperature and irradiance. In this work, the DT model is created using the current generated of modules and arrays as in equation (4). Real-time comparisons between monitored data and simulation outputs are possible with this experimental platform. In fact, it might be applied to provide new approaches for problems with fault detection and prediction. The generated digital twin's accuracy was evaluated using the correlation coefficient $R^2$. A small moving window is chosen to calculate this coefficient instead of the assessment for the whole period. This window-based calculation is important to monitor the fitting of the created digital twin model as well as observe any deviation that may be produced due to faults in the physical system. The $R^2$ coefficient using a moving window of samples $m$ between the physical observed output $Y$ and the twin output $Y^*$ as in (5).

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{m}\left(Y_i - Y_i^*\right)^2}{\sum_{i=1}^{m}\left(Y_i - \bar{y}\right)^2}\right] \tag{5}$$

where $Y_i$ is the physical output at instant or sample $i$, $Y_i^*$ is the twin output at the same instant, and $\bar{y}$ is the mean physical observed output through the time span $m$.

For a digital twin to be implemented successfully, digitalization through smart sensors and the data they generate is essential. In this work, the DT model is created and built using MATLAB/SIMULINK model running on Linux and hosted on the third machine as shown in the top of Fig. 6. Modbus TCP protocol is used to communicate between the PC that hosts the digital twin model and the emulated edge nodes in the communication network. By mapping Modbus data across the Ethernet/IP, the Modbus-to-Ethernet/IP gateway makes migration easier with its straightforward configuration.

## VI. Simulation Results and Discussion

PV plants are intricate systems with various potential sources of problems, including optical failure or degradation, electrical mismatches such as shading, broken or short-circuited bypass diodes, short-circuited modules or strings, and failure of the junction box. In general, various faults can impact photovoltaic systems and lead to a substantial loss of power. In this section, we will describe different PV system behavior testing scenarios under both normal operation and faults. These scenarios aim to measure the mismatch between the physical and the twin models and twin models and detect faults when this mismatch reaches a certain level. In this study, we will focus on the modules' short circuit and open circuit faults as shown in Fig.7.

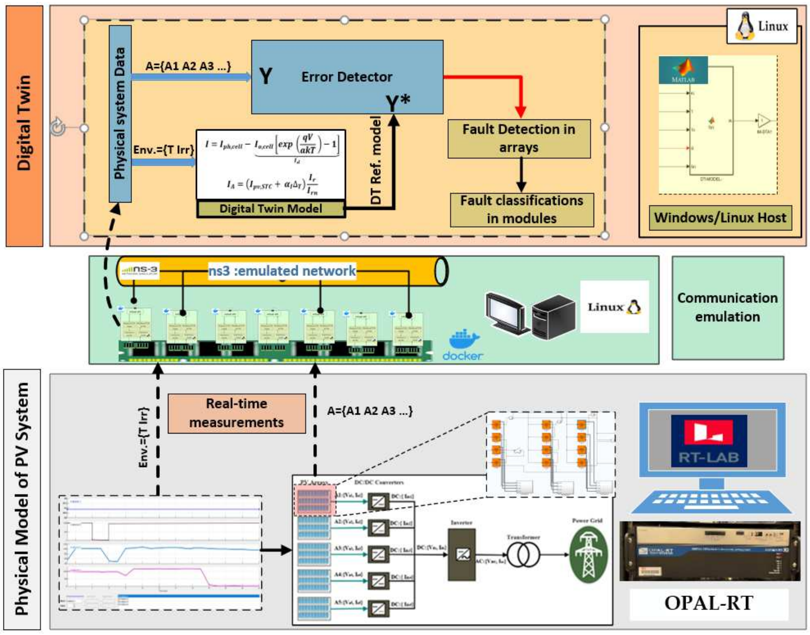


Fig. 6. The three-dimensional implementation of DT for the studied PV system

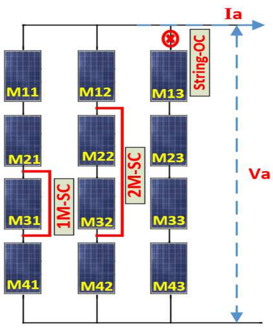


Fig. 7. Different array faults

## A. Normal operation: Studying PT and DT behaviors

One major factor influencing the current parameters is solar irradiation. More precisely, the I-V curve's maximum power point current and short circuit current both rise linearly as irradiance increases. Conversely, voltage characteristics are greatly influenced by cell temperature. Therefore, testing the behavior of the modeled physical PV system and the twin model is executed based on the input pattern of irradiance during the 24-hour (24 secs in simulation). According to the input data of the PV system (irradiance and temperature), the DT model output of PV arrays is calculated as shown in Fig. 8. By comparing the two values, ascertained the magnitude of the difference that occurs between the projected value by the twin model that was constructed to make the prediction and the actual value, or the measured output current provided by the solar arrays. Also, the comparison between the module current of one of the strings in the first array with their twins is performed in this test. The coefficient R2 between the outcomes of the digital model and the physical model for various scenarios shows the accuracy of the digital twin.

## B. Short circuit scenarios

Two categories of events can be identified based on the length of the event: those that are transient because of external factors and those that are permanent because of short circuits. In this section, testing the twin behaviors under normal, sudden environmental conditions change, and faults is performed as shown in Fig. 9. In the temporary sudden change in the irradiance, the PV system then returns to its normal operating condition. As shown in the figure, when the irradiance increases suddenly at t=8 sec, there is a small variation in the $R^2$ detector for all arrays output. This variation occurred due to the mismatch between the physical and twin models during the transient condition or transition from one state to another in a short time. So, selecting the thresholds for fault detection must be calculated based on these worst cases.

On the other hand, when the short circuit occurred on module M31 in the first array, as shown in Fig. 7, the array current IA1 decreased suddenly, and $R^2$ for the array A1 also decreased as shown in Fig. 9. To check the accuracy of the twin model, a comparison was performed between the actual model current and the twin model for each model. As shown in Fig. 10, the twin output for the faulted module current is almost the same for the physical module. This is because the output current is the *Isc,* which is almost equal to the actual output module current according to equation (4).

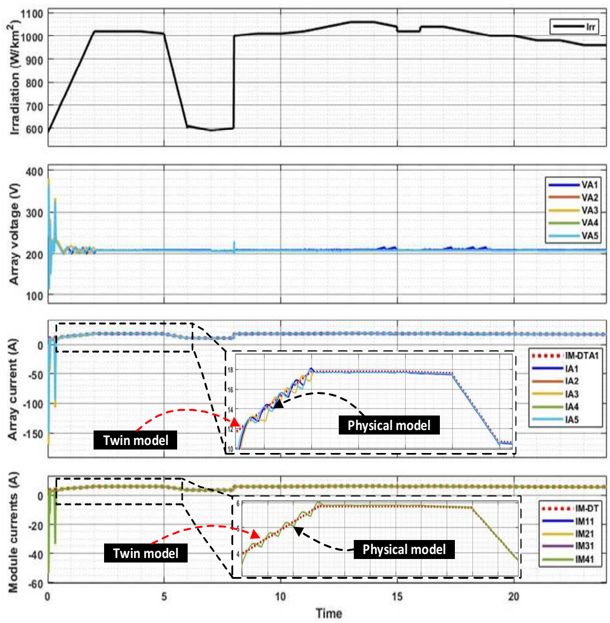


Fig. 8. Physical PV system and twin behaviours under normal operation

### C. Open circuit faults in strings

In contrast to a short-circuit fault, an open-circuit fault can happen if a closed circuit's current path that is in series with the load is inadvertently removed or opened. The primary cause of such a scenario is a break in the cable connecting PV solar cells or modules. To discriminate between the different types of short circuits on modules and string open circuits, $R^2$ is calculated and plotted based on a moving window of data. As shown in Fig. 11, three faults (1M-SC, 2M-SC, String-OC) are performed, and $R^2$. According to the records, in normal operation or normal sudden change, the value of $R^2$ is between 1 and 0.9975, which also represents the high accuracy in the digital twin model. On the other hand, during fault scenarios, we observed a sudden change in the $R^2$ with different behaviors and values less than 0.9975 based on the fault type. Based on these records, different thresholds were selected to distinguish between these faults.

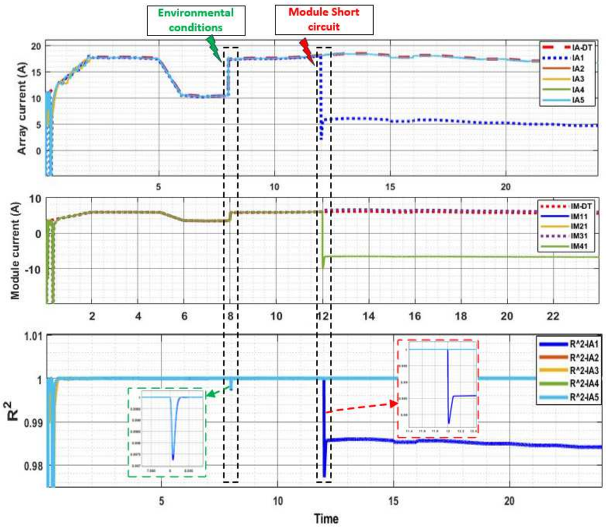


Fig. 9. PV system behaviour under fault condition if 1M-SC.

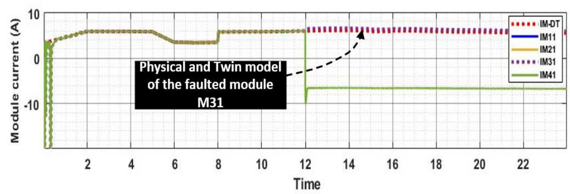


Fig. 10. Comparison of modules's currents with the twin model under 1M-SC.

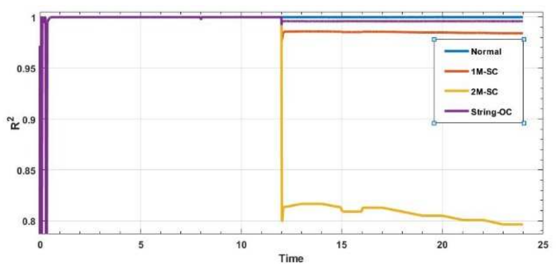


Fig. 11. $R^2$ calculation for different fault scenarios.

## VII. Conclusion

The digital twin, a dynamic virtual counterpart of a physical system, is an emerging and transforming technology that may offer PV system monitoring and event detection solutions. This work provided a new approach for diagnosing faults in PV arrays, integrating digital twinning and $R^2$ coefficient analysis for their detection and classification. With the implementation of the PV system DT platform in the ESRL testbed, the accuracy of the digital twin model is evaluated and tested. In addition, different fault scenarios were performed.

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