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# Photovoltaic System Emulation Using DC Programmable Power Supplies

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**Abstract: This paper explores a novel approach to the fast emulation of a selected photovoltaic (PV) system, leveraging DC programmable power sources to accelerate the emulation process. Traditional PV system emulation is time-consuming, as it typically requires real-time simulation of environmental factors like solar irradiance and temperature. However, by utilizing high-performance DC programmable sources, the emulation time is significantly reduced, making it possible to predict daily electricity generation in a much shorter timeframe. This advancement enables the rapid evaluation and comparison of various photovoltaic systems, including systems with different power ratings and PV module configurations. Additionally, by simulating the electrical energy output of these systems, valuable insights can be gained to guide the selection of the most suitable photovoltaic system for specific regional climates. The paper also highlights the potential of this fast emulation method to optimize the design and implementation of PV systems, improving energy efficiency and performance. The emulated data generated can be used to make informed recommendations regarding the choice of an optimal photovoltaic system based on the climatic conditions of the region in question.**
**Keywords – DC programmable sources, emulated electrical energy, fast emulation, operational scripts, PV emulator, photovoltaic systems, solar power generation, climate-based optimization.**

## 1. Introduction:

The global growth of renewable energy sources has been remarkable in recent years, with photovoltaic (PV) systems being at the forefront of this transition. According to the annual report on renewable energy sources, a total of 227 GW of PV systems were installed in 2015 alone, and this capacity has been steadily increasing each year by 30-50 GW [1]. The primary drivers of this expansion include the significant reduction in the costs of photovoltaic module manufacturing and advancements in power electronics, which have made PV technology more accessible and cost-effective [2].

However, testing the electronic equipment that connects PV modules to the grid, such as inverters, and evaluating electricity generation across different PV module technologies, requires reliable testing systems. These systems must function independently of daily solar power availability and the constraints of physical space, such as rooftops. This necessity has led to the development of photovoltaic emulators, which replicate the electrical characteristics of PV modules and allow for controlled simulations of PV system performance. These emulators enable researchers and engineers to test and simulate the performance of PV systems without relying on actual sunlight or physical installations.

PV emulators can be built using various approaches, with one common method involving mathematical modeling of PV modules. In this case, simulation tools such as MATLAB or LabVIEW are used to generate the mathematical models of the PV system, which then serve as inputs to the hardware of the emulator [3-5]. This approach typically scales electrical quantities like voltage and current to levels that are safe for handling and easy to measure, making the emulation process more affordable and feasible. However, while this technique has been widely used to emulate individual PV modules, there is a lack of research focused on emulating entire PV systems to predict electricity generation on a larger scale.

To address this gap, the paper proposes a novel energy-based concept for PV emulation. Instead of scaling electrical quantities, real voltage-current (V-I) characteristics of PV modules or strings are retrieved from a database and used as inputs to programmable DC power sources. These programmable sources are capable of replicating the V-I characteristics of the PV modules, which are then used to supply the PV grid-connected inverter. This method allows for the emulation of electricity generation over an extended period, making it possible to predict the energy output of different PV systems in a fraction of the time typically required for traditional emulation.

The fast emulation method discussed in this paper significantly reduces the time required for emulating a PV system's electricity generation, enabling daily predictions to be made in a fraction of the time needed for conventional emulation. This is accomplished by using operational scripts for programmable DC sources, which automate the input of voltage and current values and allow simultaneous operation of multiple sources in the PV emulator. The fast emulation method is validated by using data from the ETFOS1-10kWp solar power plant, where the emulated electrical energy was compared with actual electricity generation from the plant. The results show that fast emulation can accurately estimate the energy production of PV systems on days with varying levels of solar irradiance.

This paper is organized as follows: Section 2 introduces the technical characteristics of the laboratory PV emulator used in the study. Section 3 discusses the limitations of obtaining accurate PV emulation with the chosen laboratory setup. In Section 4, the application of fast PV emulation to a selected photovoltaic system is presented. Finally, Section 5 concludes the paper and summarizes the key findings and implications of the study.

## 2. PV EMULATOR

A Photovoltaic (PV) emulator is an essential tool for simulating the behavior of photovoltaic systems without relying on actual solar irradiance. It consists of several key components that allow for precise replication of the electrical characteristics of PV modules and strings. These components include programmable DC sources, an inverter, a junction box with protective devices, an electronic digital watt-hour meter, and a metal case that houses all the subsystems and connecting cables. Each of these subsystems plays a crucial role in ensuring the emulator functions efficiently and accurately.

### 2.1. PROGRAMMABLE DC SOURCES

The heart of the PV emulator is the programmable DC sources. These sources emulate the voltage-current (V-I) characteristics of photovoltaic strings, replicating the output characteristics of real PV modules. One of the primary programmable DC sources used in this system is the LAB/HP 101000, which is widely known for its high precision and reliability.

The key technical specifications of the LAB/HP 101000 are outlined in Table 1, and they provide the foundation for the operation of the emulator. The programmable DC sources are designed to work seamlessly with other components in the system to emulate a variety of PV system characteristics.

**Table 1: Technical Characteristics of LAB/HP 101000**

| Characteristic | Value |
|---|---|
| Maximum source voltage | 1000 V |
| Maximum source current | 10 A |
| Connection to AC network | Three-phase |
| Input frequency | 47-63 Hz |
| Input voltage range | 230VAC / 3x208VAC / 3x480VAC ± 10% |

The LAB/HP 101000 programmable DC sources can be configured in parallel or series circuits, also known as master-slave mode. This flexibility allows the voltage and current ranges of the sources to be expanded, making them adaptable to different PV system configurations. Five operational modes are available for various simulation needs, as shown in Table 2.

**Table 2: Modes of Operation of DC Sources**

| Mode of Operation | Characteristics |
|---|---|

| | |
|---|---|
| UI | Voltage and current limit |
| UIP | Voltage and current limit based on set power |
| UIR | Voltage and current limit with simulated internal alternating resistance |
| PVsim | Simulation of photovoltaic characteristic |
| Script control using a memory card | Allows script-based control using memory card |

For the purpose of emulating PV systems, the **PVsim** mode is specifically utilized. This mode accurately simulates the photovoltaic characteristics of solar panels based on real-world conditions, including voltage, current, and power generation profiles.

### 2.2. INVERTER

The inverter is another crucial component in the PV emulator system. It serves the purpose of connecting the programmable DC sources, which emulate the characteristics of PV modules, to the power distribution network. This connection is necessary for interfacing the generated power with the grid and ensuring the proper functioning of the entire system.

A photovoltaic inverter is responsible for Maximum Power Point Tracking (MPPT), which optimizes the energy harvested from the simulated PV system by continuously adjusting the operating point to maximize power output. The inverter used in this emulator has two input ports, each capable of receiving power from a different programmable DC source. This dual-input configuration allows for the simulation of two distinct PV strings or systems, which can be particularly useful in emulating complex PV installations or systems with multiple string configurations.

For the purpose of fast emulation, one programmable source is connected to each input port of the inverter. The inverter also features a built-in saving function that records input and output data over a specified time interval (ranging from 1 to 30 minutes). These data points, including voltage, current, and power, can be downloaded onto a computer via a USB drive for further analysis and comparison.

The inverter is crucial in the PV emulation process as it not only controls the operation of the PV strings but also ensures that the characteristics of the emulated PV modules are appropriately adjusted for real-world conditions. By saving and downloading data, the inverter enables researchers and engineers to assess the performance of the emulated system and make informed decisions about PV system optimization and efficiency.

The PV emulator system is built around programmable DC sources, which replicate the electrical characteristics of real PV modules, and an inverter that ensures proper integration of the emulated system with the power grid. With the ability to simulate different PV system configurations and operation modes, the PV emulator enables efficient testing and evaluation of PV systems in a controlled, reproducible environment. The fast emulation approach, using operational scripts and data saved by the inverter, further enhances the emulation process, reducing time and effort while maintaining accuracy.

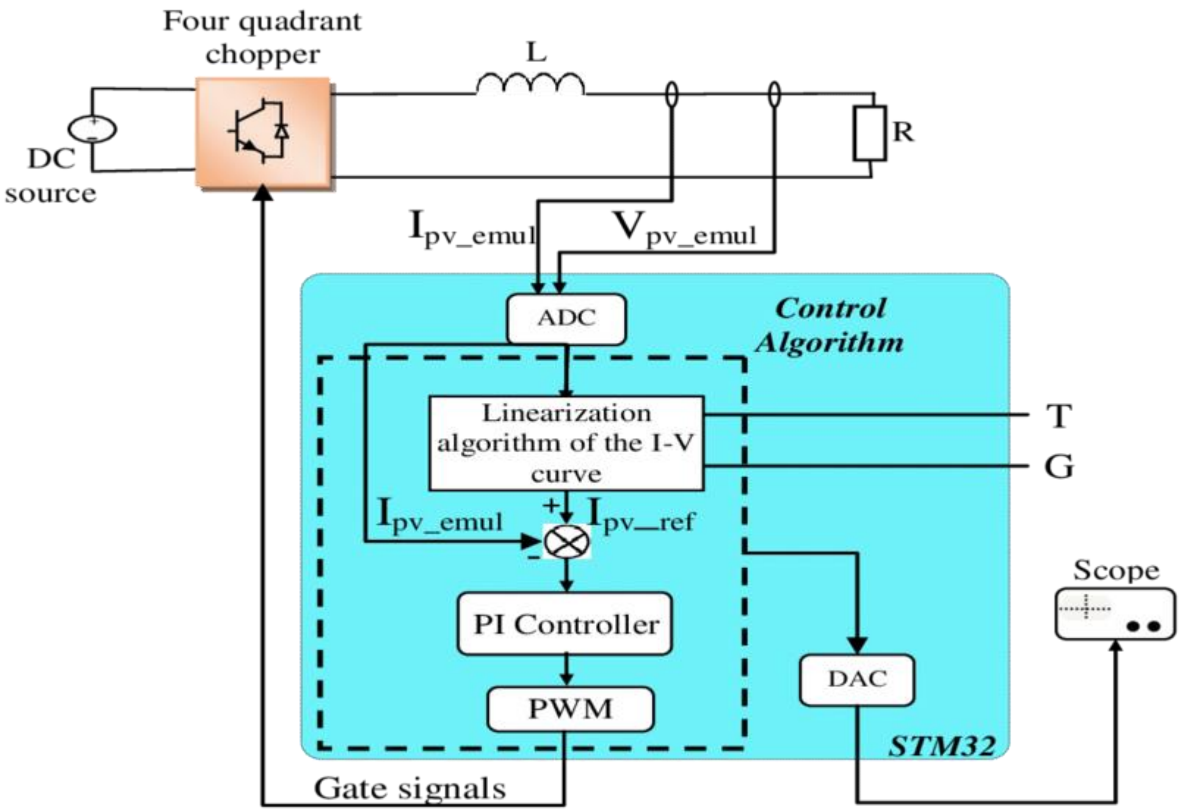



Fig 1. PV emulator

### 2.3. DIGITAL WATT-HOUR METER

To accurately determine the emulated power output of the photovoltaic system during the emulation process, a digital watt-hour meter is utilized. This meter plays a crucial role in providing precise measurements of the energy generated by the system, ensuring that the data collected during the emulation reflects the true performance of the PV system.

The digital watt-hour meter, as shown in Figure 2, is connected at the inverter end of the system. The meter is designed with high resolution, offering a precision of up to 0.01 kWh, or 10 Wh. This level of precision is essential, especially for detecting and measuring atypically low energy production values, which are often observed in PV systems under certain environmental or operational conditions.

The ability to measure low production values accurately ensures that even minor fluctuations in power output can be captured. This is particularly important when performing fast emulation, as the evaluation of the system's performance across different times of day or varying irradiance levels requires detailed and precise energy data.

By utilizing this meter, the emulated electrical energy can be monitored and evaluated in real-time, providing an effective means of assessing the efficiency of the PV emulator and the overall performance of the simulated photovoltaic system.

The system connection for the digital watt-hour meter is depicted in **Figure 2**, which illustrates how the meter interfaces with the inverter and the overall PV emulator setup.

This setup allows for reliable data collection and analysis, ensuring that the emulated electrical energy corresponds closely with the expected performance of actual PV systems, facilitating the optimization and comparison of different PV modules and system configurations.

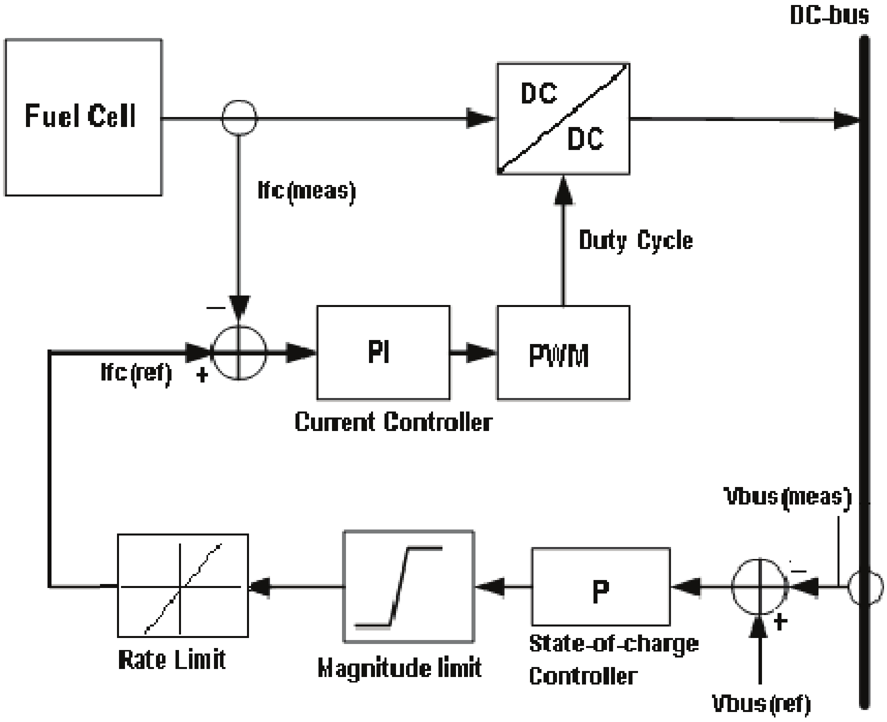



Fig 2. Schematic connection of PV subsystems

### 3. LIMITATIONS OF A PV EMULATOR

While the proposed smart-fast emulation method for PV system simulation provides an efficient means of emulating photovoltaic systems with reduced time and increased accuracy, it is not without limitations. These limitations primarily stem from the constraints of the programmable DC sources and the scripting mechanism used to manage the emulation process. The script-based control of the emulation involves invoking the PVsim mode, which is managed by a memory card storing predefined commands that control the operation of the programmable DC sources. The following sections detail the limitations encountered when using this approach.

### 3.1. THE MAXIMUM NUMBER OF SCRIPT COMMANDS

One of the key limitations of the proposed emulation approach is the restriction on the number of script commands that can be executed by the programmable DC source. As tested during the development of the emulation system, the maximum number of commands that can be included in a single script for the LAB/HP 101000 programmable DC source is **35** commands. Each command in the script corresponds to a specific voltage-current (v-i) characteristic for the emulated photovoltaic module or string.

In the PVsim mode of operation, each command requires 7 lines of code to define the v-i characteristic of a module or string, as shown in **Figure 3**. This means that with the limitation of 35 commands, the maximum number of v-i data points that can be included in a single script is limited to 245 (35 commands × 7 lines per command).

If the number of commands exceeds this limit, the system will display an error message: “Too many commands!” and the script will fail to complete. This limitation restricts the complexity and granularity of the emulation, particularly for more detailed or longer-duration emulation tasks.

This constraint is determined by the manufacturer of the DC programmable source and cannot be altered by the user. Therefore, when developing scripts for emulation, it is essential to ensure that the number of commands remains within this maximum limit to avoid errors during the emulation process. Consequently, the user may need to adjust the resolution of the data or the time intervals used in the script to remain within the allowed limits, which could potentially compromise the accuracy of the emulation for highly dynamic or long-duration simulations.

Overall, while the script-based approach for fast PV emulation offers significant time savings compared to traditional methods, the restriction on the number of commands and the associated limitations in the duration and resolution of the emulation must be considered when planning and executing PV system emulations.

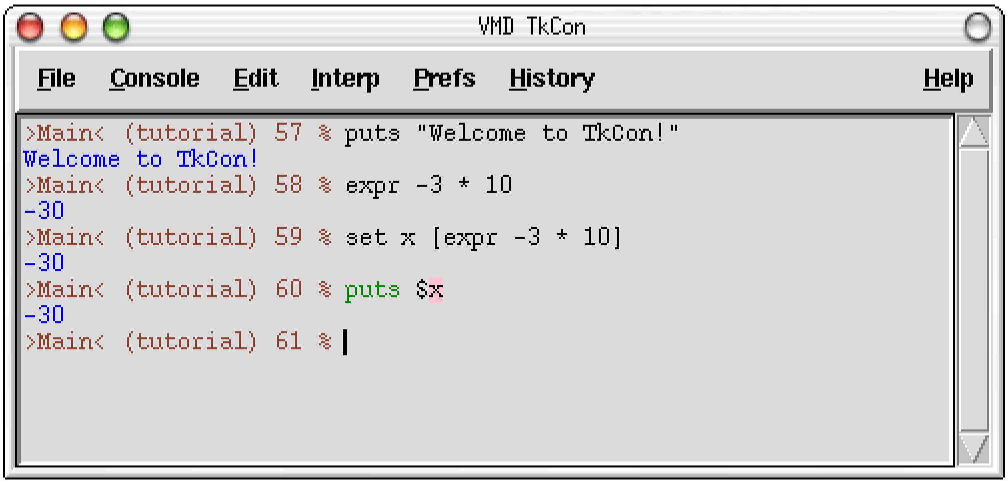



Fig. 3. An example of script command number testing and duration of a single command

### 3.2. THE MAXIMUM TIME INTERVAL OF SCRIPT COMMANDS

Another critical limitation encountered in the fast PV emulation process is the restriction on the maximum time interval that can be set between consecutive script commands. The script uses a predefined subcommand called "Delay" to specify the time interval between commands. Testing the emulation process revealed that the maximum time interval allowed for a command is **65,000 ms** (or **1 minute**). This time interval represents the upper limit that can be set for the delay between commands.

If the user attempts to set a time interval that exceeds 65,000 ms, the DC programmable source will automatically reset itself to its default settings. This is due to the source's internal timing mechanism, which is designed to execute commands at a rate much faster than the maximum allowable duration. As a result, the system will continue to execute commands at a significantly shorter time interval than what was specified, leading to potential errors and disruptions in the emulation process.

The **Figure 4** and **Figure 5** below demonstrate the typical daily power diagrams for both sunny and cloudy days, with the appropriate time intervals taken into consideration for each scenario. The impact of this time interval limitation is particularly relevant when simulating longer-duration emulations or when the granularity of time data is crucial to the accuracy of the simulation.

## 4. FAST PV EMULATION

In order to perform a fast and efficient simulation of a selected PV system, it is essential to have access to a well-documented and accurate database of the v-i characteristics of PV modules and strings. During the course of this project, a solar power plant named **ETFOS1** was established. This plant consists of two strings, each containing 20 photovoltaic modules with different technologies: **BISOL BMU-250** (polycrystalline) and **BISOL BMO-250** (monocrystalline). Additionally, a comprehensive database of the measured v-i characteristics of these PV modules was created [18].

The next step in the emulation process involves preparing the necessary entry data for input into the DC programmable sources. This data includes the following key parameters:

- **I_mppn**: Current at the maximum power point for the nth string
- **V_mppn**: Voltage at the maximum power point for the nth string
- **V_ocm**: Open-circuit voltage of the m-technology string

- **I_scm**: Short-circuit current of the m-technology string

These parameters were gathered from the inverter of the ETFOS1 photovoltaic system and the database of module characteristics. The data collection was performed at **5-minute intervals** over a period of several days. To ensure the reliability of the data, the emulation process was carried out for **sunny days** (with stable solar irradiation) and **cloudy days** (with significant fluctuations in solar irradiation).

In particular, **3 sunny days** (November 2, 3, and 12, 2014) and **3 cloudy days** (April 19, May 12, and May 25, 2016) were selected for comparison. These days offered a good mix of stable and variable solar irradiation, enabling the emulation system to predict and compare power generation under different environmental conditions. The results of the emulation were expressed as **electricity generation (W_tot)** over the course of the day.

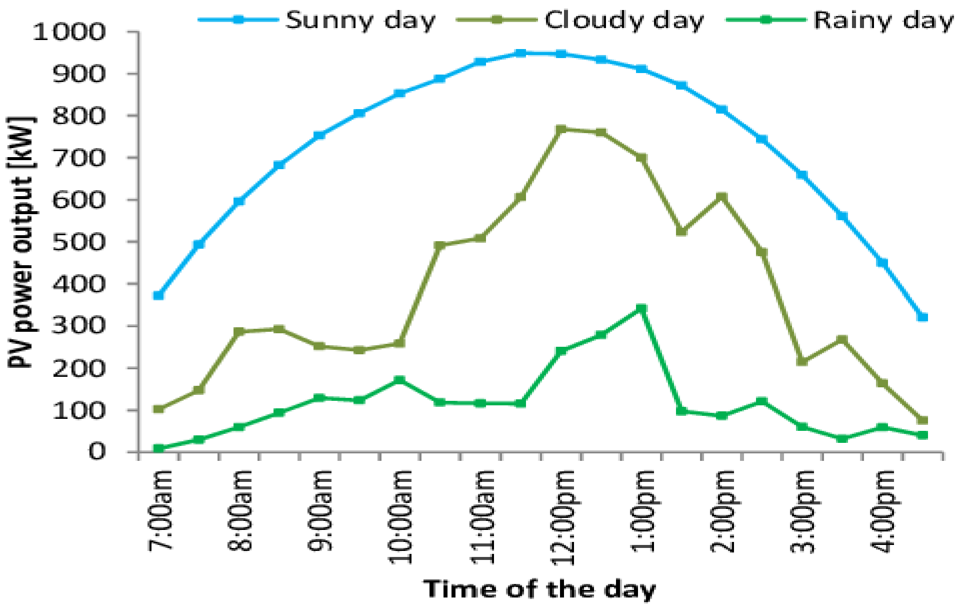



**Figure 4: Power Generation on a Sunny Day**

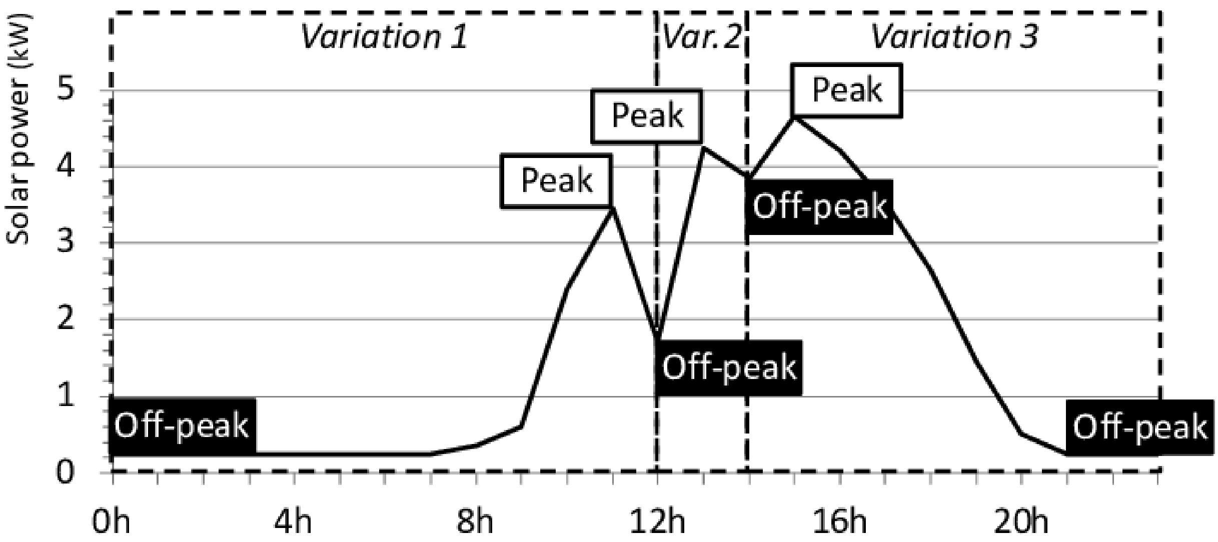



**Figure 5: Power Generation on a Cloudy Day**

These emulated power generation diagrams were compared with actual electricity generation data collected from the inverter of the ETFOS1 solar power plant. This comparison allowed for the validation of the fast emulation process, ensuring that it could accurately predict power generation for both steady and fluctuating solar conditions. The emulation was shown to produce results that were comparable to the actual system output, demonstrating the effectiveness of the fast PV emulation method.

#### 4. Fast PV Emulation Results

The results of fast PV emulation show a significant reduction in emulation time compared to the standard emulation process. On a typical sunny day, standard emulation would require **9 hours and 30 minutes**, while the fast emulation method only takes approximately **20 minutes**. This drastic reduction in time is especially beneficial for simulating large-scale photovoltaic systems or for scenarios requiring multiple emulation runs to evaluate different system configurations. On certain spring days, such as April 19, the standard simulation time can exceed **12 hours** due to the longer periods of sun exposure and power output variability. By utilizing the fast emulation approach, this time is significantly minimized, providing quicker insights into the energy production capabilities of a given PV system.

#### Comparison of Emulated and Actual Energy Production

Based on the comparison of characteristic values taken from the power plant inverter (shown in **Table 3**) and the emulated values obtained from the PV emulator (shown in **Table 5**), it was observed that the **maximum power point tracking (MPPT)** inverter system did not always maintain the operating point at the maximum power point (MPP) during the morning and evening hours. During these periods, the power produced was lower (less than 100 Wh), and as a result, the **DC programmable sources** did not precisely match the v-i characteristics that correspond to the maximum power output.

This discrepancy aligns with the technical specifications of the inverter, where MPPT efficiency may be compromised under low irradiation conditions. As a result, the emulated energy output (**W_em**) was consistently lower than the actual energy production (**W_an**). This finding is expected, as the fast emulation system aims to provide an estimate, and in cases of low irradiation, some loss is inevitable due to imperfect MPPT tracking.

#### Final Results of Fast Emulation

The results of the emulation for both sunny and cloudy days, along with the relative errors, are summarized in **Table 6**. For each day, the **total electrical energy generated (W_tot)** is compared to the **measured energy from the inverter (W_an)** and the **emulated energy (W_em,count)**. The relative errors (**δ_em**) were calculated for both sunny and cloudy days using the following formulas:

- For a sunny day:
- $\delta ems = \mid Wem - Wan \mid Wan \times 100\% \delta_{\{em_s\}} = \backslash frac\{|W_{\{em\}} - W_{\{an\}}|\}\{W_{\{an\}}\} \times 100 \, \backslash\% \delta ems = Wan \mid Wem - Wan \mid \times 100\%$
- For a cloudy day:

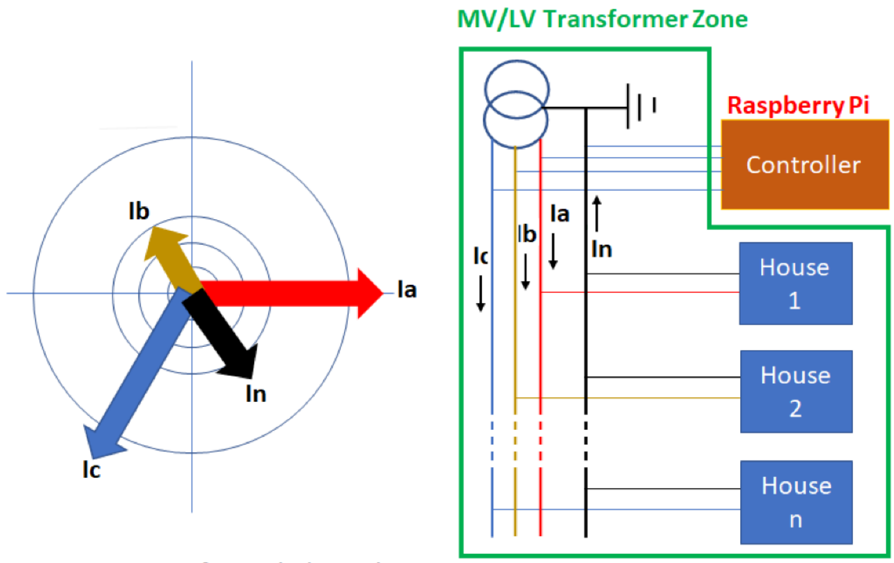
$$\delta emc = \mid Wem - Wan \mid Wan \times 100\% \delta_{\{em_c\}} = \backslash frac\{|W_{\{em\}} - W_{\{an\}}|\}\{W_{\{an\}}\} \times 100 \, \backslash\% \delta emc = Wan \mid Wem - Wan \mid \times 100\%$$

**Table 6: Emulated Energy and Relative Error**

| Date | W_tot (Sunny) [kWh] | W_tot (Cloudy) [kWh] | W_an (kWh) | W_em,count (kWh) | δ_em (Sunny) [%] | δ_em (Cloudy) [%] |
|---|---|---|---|---|---|---|
| **2 Nov** | 21.71 | / | / | 21.3 | +1.8 | / |
| **3 Nov** | 23.36 | / | / | 23.1 | +1.1 | / |
| **12 Nov** | 34.00 | / | / | 33.17 | +2.4 | / |
| **19 Apr** | / | 11.18 | 12.49 | 10.5 | / | +6.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **12 May** | / | 15.7 | 15.7 | 14.7 | / | +6.3 |
| **25 Feb** | / | 11.18 | / | 10.5 | / | +6.5 |

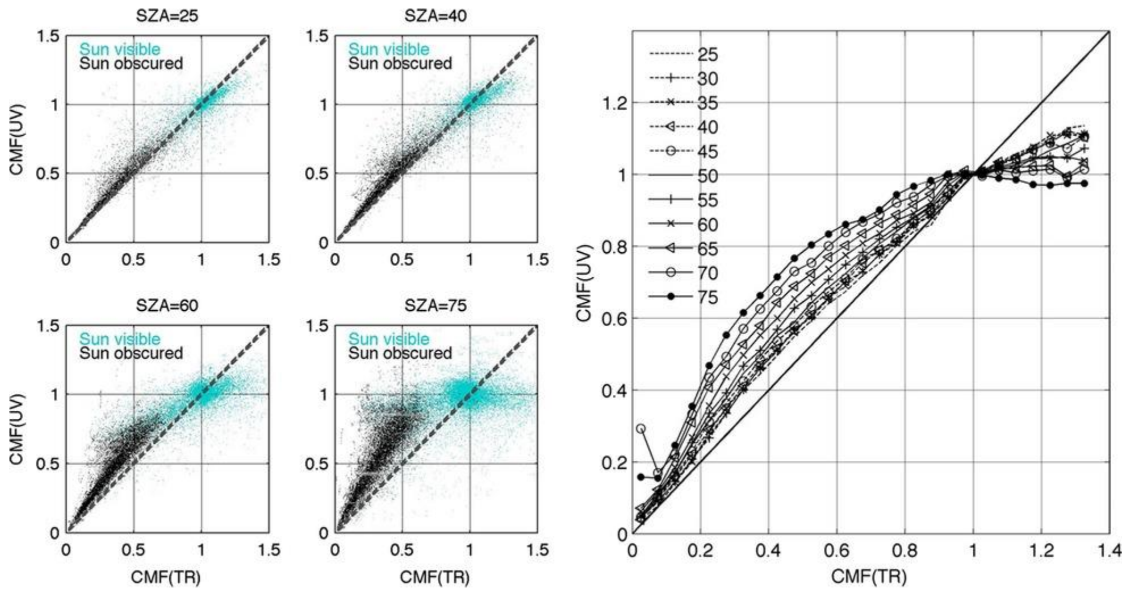
**Figures 6 & 7: Electrical Energy and Relative Error**




Current Vectors of an unbalanced System (Phase: A = C; B<A; B<C)

Typical Three Phase Supply to Individual Single-Phase Consumers

- **Figure 6** illustrates the characteristic electrical energy and relative error for sunny days, showing how the emulated energy closely follows the actual energy produced, with a deviation of at most 3%.




- **Figure 7** presents the data for cloudy days, where the deviations are slightly more noticeable but remain below 7%. The deviations on cloudy days are typically higher because of the fluctuations in solar irradiation, making it more difficult for both the emulated system and the actual system to track power output with precision.

The results confirm that **fast PV emulation** is a valuable tool for estimating the energy production of photovoltaic systems, especially when comparing systems with varying power outputs or module technologies. The **relative error** in the emulation results is minimal for sunny days, with errors typically within **3%**. On cloudy days, where solar irradiation fluctuates, the relative error can be as high as **6-7%**, but still within an acceptable range for most applications.

The fast emulation method proves to be effective for evaluating daily and monthly energy production from different PV systems, facilitating the comparison of systems with diverse power ratings and module types. As long as a reliable database of v-i characteristics is available, fast emulation can offer accurate and timely predictions for PV energy production.

## 5. CONCLUSION

This paper successfully demonstrated the fast emulation of the photovoltaic system ETFOS1 over six days, both with and without significant changes in solar irradiation. The system under test consisted of two strings of 20 photovoltaic modules each, employing polycrystalline and monocrystalline module technologies. The fast emulation approach was based on v-i characteristics obtained from a comprehensive database.

A key result of this study is the reduction in emulation time from the typical **9.5 hours** required for standard emulation to just **20 minutes** for a selected winter day with stable solar conditions. This dramatic decrease in emulation time significantly enhances the efficiency of evaluating PV systems. The comparison between the measured and emulated electrical energy production on a sunny day showed a relative error of just **1.8%**, which confirms that the fast emulation approach provides highly accurate results, justifying its application for estimating the electrical energy output of photovoltaic systems.

In scenarios where solar irradiation fluctuates, such as on cloudy days, the relative error in the emulated power was slightly higher, reaching up to **7%**. While this deviation is noticeable, it remains within an acceptable range for most practical applications. The error behavior indicates that even on days with significant changes in solar irradiation, the fast emulation method can still provide valuable predictions of PV system performance.

The results of this study validate the fast emulation method as a practical and efficient tool for estimating the daily electrical energy production of various photovoltaic systems, regardless of their size or module technology. Moreover, this approach can be extended to monthly evaluations, helping to optimize the selection of photovoltaic systems based on climate conditions and regional characteristics. The fast emulation method, with its reduced computation time and reliable accuracy, holds the potential to assist in making well-informed decisions regarding the most suitable PV systems for a given location.

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