

INTERNALLY RECONFIGURED SMART PHOTOVOLTAIC SOURCES

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Abstract. This paper examines the design principles of smart photovoltaic power sources. It explores the devices that transform traditional photovoltaic sources into smart electrical energy systems and describes the hardware required to implement these intelligent functions. The study investigates the structural principles of photovoltaic sources with reconfigurable internal topologies. It demonstrates the feasibility of employing switched connections instead of fixed wiring for interconnecting solar cells within a panel, noting that such connections can be dynamically controlled. The use of field-effect transistors is identified as the most suitable switching element. The paper contrasts the conventional approach, where source topology is modified by connecting or disconnecting individual photovoltaic cells, with an alternative method utilizing a switching unit to arrange elements in parallel or series configurations. A practical implementation of a photovoltaic panel is proposed, featuring cells interconnected via commutation cells under the control of a programmable microcontroller. Furthermore, the principle of forming an electrical grid incorporating these smart photovoltaic panels is presented. Two distinct configurations are realized: one utilizing traditional communication networks and another employing hybrid power-communication lines and devices. Key advantages of smart photovoltaic sources are highlighted, emphasizing that power systems equipped with such sources benefit from the dynamic optimization of generation parameters. Finally, the principles for developing a data exchange communication protocol between smart photovoltaic sources are described, followed by concluding remarks.

Key words: smart energy, photovoltaic source, internally reconfigurable source, solar panel, solar cell.

ВНУТРІШНЬО ПЕРЕКОНФІГУРОВАНІ ІНТЕЛЕКТУАЛЬНІ ФОТОЕЛЕКТРИЧНІ ДЖЕРЕЛА

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Анотація. У роботі розглядаються принципи побудови інтелектуальних фотоелектричних джерел. Розглянути пристрої, за допомогою яких, традиційне фотоелектричне джерело стає інтелектуальним джерелом електричної енергії. Описано необхідне обладнання для реалізації джерел з інтелектуальними функціями. Розглянуті принципи побудови фотоелектричних джерел зі змінною внутрішньою топологією. Показана можливість застосування для з'єднання фотоелементів в панелі замість фіксованих з'єднань, комутованих з'єднань. Відмічено що такі з'єднання можуть керуватись динамічно. Відмічено, що в якості ключів доцільно використовувати польові транзистори. Показано традиційний підхід, в якому топологія джерела міняється за рахунок приєднання та від'єднання фотоелектричних елементів, а також показано альтернативний шлях побудови джерел з використанням комутаційного вузла, який з'єднує елементи паралельно чи послідовно. Запропонована реалізація фотоелектричної панелі з елементів, які з'єднані за допомогою комутаційної комірки під керуванням програмно керованого мікроконтролера. Показано принцип утворення електричної мережі, яка містить інтелектуальні фотоелектричні панель. Реалізовано два варіанти, один за допомогою традиційних комунікаційних мереж, інший за допомогою комбінованих електрично-комунікаційних ліній та засобів зв'язку. Акцентовано на ключових перевагах інтелектуальних фотоелектричних джерел. Відмічено, що перевагою енергетичних систем з такими джерелами є динамічна оптимізація генераційних параметрів. Описані принципи побудови комунікаційного протоколу обміну даними між інтелектуальними фотоелектричними джерелами. Зроблені висновки.

Ключові слова: інтелектуальна енергетика, фотоелектричне джерело, внутрішньо переконфігуроване джерело, сонячна панель, сонячний елемент.

Introduction

The advancement of solar energy and its integration into various sectors of the economy and industry necessitate comprehensive and in-depth scientific research focused on the efficiency and versatility of such power sources [1, 2]. Accordingly, the deployment of diverse energy solutions driven by industrial and consumer demand prompts research into the flexibility and controllability of power sources. On the other hand, progress in microcontroller technology and communication systems enables the integration of digital intelligence directly into these sources, facilitating the development of integrated smart energy solutions. Furthermore, solar energy sources are highly conducive to the implementation of smart solutions, as they consist of arrays of individual generating units that allow for flexible control and management.

The core concept of this research is that a smart solar source is not merely a silicon wafer generating current, but a comprehensive system integrated with electronics to optimize performance at the level of each individual module or panel.

Objective

The objective of this research is to leverage variable internal source topology to develop photovoltaic modules and panels that align with modern smart technology standards, specifically regarding versatility, controllability, and communication capabilities.

Methods and materials. System Components and Key Technologies

For a photovoltaic source to become 'smart,' it must move away from the traditional design principle of fixed output parameters and be equipped with additional electronic and power switching hardware. The transition of a conventional PV source into an 'smart' one is facilitated by the integration of the following devices: Power Optimizers for Maximum Power Point Tracking (MPPT); microinverters to convert direct current (DC) to alternating current (AC) directly within the generator, effectively turning the source into an independent power plant; and monitoring and communication systems (such as Wi-Fi, Zigbee, or PLC) for data transmission. Notably, unlike traditional systems where multiple panels are connected into a single string, smart panels possess their own 'brains' in the form of MLPE (Module-Level Power Electronics) [3, 4].

The paper proposes moving away from external electronic devices by delving into the internal circuitry of the source, integrating many of the aforementioned devices directly into the topology of generating electrical circuits, or replacing certain necessary components by modifying output parameters through changes in internal topology. Thus, the internal circuitry of a smart source can be either a combination of a classical semiconductor photovoltaic structure

and an integrated MLPE module [5], or a combination of switching units with a control module for dynamic topology modification and a communication device. In other words, the electronic architecture of a smart PV panel consists of internal switching elements or external power control elements, a communication and telemetry unit, and, if necessary, an AC conversion unit.

Internal Cell Commutation.

A standard photovoltaic (PV) panel consists of 60 or 72 solar cells connected in series to form groups known as sub-strings. In conventional modules, these connections are established via a busbar integrated with bypass diodes, typically featuring three Schottky diodes within the junction box. In contrast, smart panels utilize active MOSFET-based bypass controllers instead of passive diodes. These controllers exhibit a significantly lower forward voltage drop, thereby minimizing the formation of hotspots and reducing power losses under partial shading conditions. This configuration establishes an internal source topology that facilitates the connection or disconnection of an individual generating cell to a sub-string, as well as the integration of strings into the panel (Fig. 1) [6].

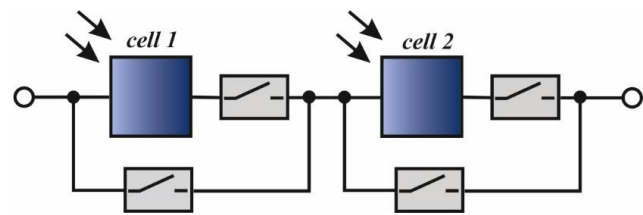


Fig. 1. Connection of photovoltaic cells to a busbar

An alternative approach involves cell switching based on a topology that enables the direct parallel or series connection of a power cell within a panel to other generating elements. In this configuration, switching occurs between the individual cells themselves rather than through a common busbar (Fig. 2).

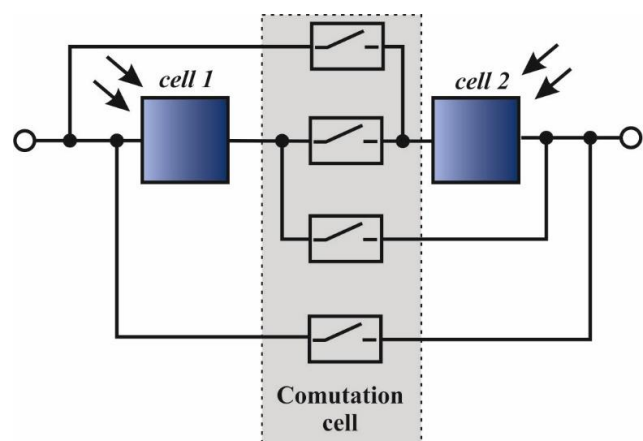


Fig. 2. Connection of photovoltaic cells by a commutation cell

The principles of dynamic change in the internal source topology, as presented in Figure 1 and Figure 2, are fundamentally different and can be applied either independently or in combination, depending on the required output parameters of the power supply. It is appropriate to utilize MOSFETs as switches due to their numerous advantages [7]. Notably, the switching principle illustrated in Figure 2 can be effectively implemented by forming switching nodes— commutation cells — which significantly simplifies the fabrication, modeling and simulation of such power sources [8].

External Power Control. Architecture of the Integrated Optimizer (DC/DC)

The majority of smart panels integrate an optimizer directly into the Junction Box. The circuit architecture consists of the following components:

- A high-frequency pulsed converter [9], which includes an input filter (low ESR capacitors designed to smooth ripples from the photovoltaic cells);
- A power stage (Buck-Boost or Interleaved Buck), utilizing MOSFETs with low channel resistance. In high-end models, Gallium Nitride (GaN) transistors are employed to operate at frequencies of 200–500 kHz, thereby allowing for a reduction in the size of the inductors [10]. The primary function of this stage is to modulate the panel's output voltage to ensure that the product $P = VI$ remains maximized, regardless of the load on the entire string;
- A microcontroller unit (MCU) [11], which executes the Maximum Power Point Tracking (MPPT) algorithm [12, 13] and analyzes the current-voltage characteristic (IV-curve) every few milliseconds.

Communication and Telemetry Block

This component of the circuit, which is absent in conventional panels, is responsible for the system's "intelligence." It comprises:

- A communicator, which may be a standard unit requiring a separate communication line or a Power Line Communication (PLC) modem [14]. The latter overlays a high-frequency data signal onto the DC power wires, enabling the transmission of voltage, current, and temperature data to the central inverter without additional wiring [15, 16];
- A temperature sensor, integrated directly into the circuit board or attached to the backsheet of the panel to monitor for overheating;
- A Rapid shutdown unit, a safety circuit that fully opens the circuit upon receiving a "safety" signal, thereby de-energizing the entire rooftop system via a power switch [17, 18].

AC Generation Block (Microinverter)

In the case of an AC inverter [19, 20], the system incorporates a full-scale two-stage converter consisting of:

- A DC/DC Isolation Stage, featuring a high-frequency transformer for galvanic isolation and stepping up the voltage to 380V;
- A DC/AC Inverter Stage, utilizing a full-bridge (H-Bridge) configuration with IGBTs or MOSFETs to generate a pure sine wave;
- An EMI Filter, designed to suppress electromagnetic interference and prevent the panel's operation from introducing "noise" into the domestic grid.

The primary challenge associated with this circuit design is reliability. The electronics must operate on high-temperature rooftops (70–80°C) for a lifespan of 20–25 years. Consequently, all components must undergo rigorous certification (Automotive or Industrial grade), and the printed circuit board (PCB) is typically encapsulated in a special compound to provide protection against moisture and vibrations. Furthermore, the self-consumption of energy by these devices must be minimized to avoid compromising the overall efficiency and advantages of the system.

To connect multiple panels equipped with microinverters, it is necessary to implement a synchronization or grid-entry device, which can be either a standalone unit or integrated into the MCU or communication block [21, 22].

Results

Based on the principles of dynamic photovoltaic cell commutation described above, this study implemented a practical circuit (Fig. 3) comprising eight power elements connected via controlled switching units. This configuration enables dynamic modifications to the internal source topology, thereby facilitating the attainment of the required output parameters.

It should be noted that for parallel connections within a series-parallel switching cell, it is necessary to employ pairs of back-to-back transistors, as field-effect transistors contain an inherent body diode [23]. A critical component of the proposed system is the microcontroller unit (MCU), which manages the switching of the transistors according to a pre-defined algorithm. To perform this function, a programmable logic controller [24] based on ARM processors [25], like STM32 or Atmel microcontrollers [26, 27], or similar platforms may be utilized.

These controllers can be directly interfaced with the field-effect transistors, as specific transistor series feature logic-level gates (5V), which is standard for the outputs of the aforementioned MCUs. Furthermore, the primary function of such a controller is to acquire data regarding the state of the source elements, specifically monitoring the generated voltage and current for both individual cells and groups of elements.

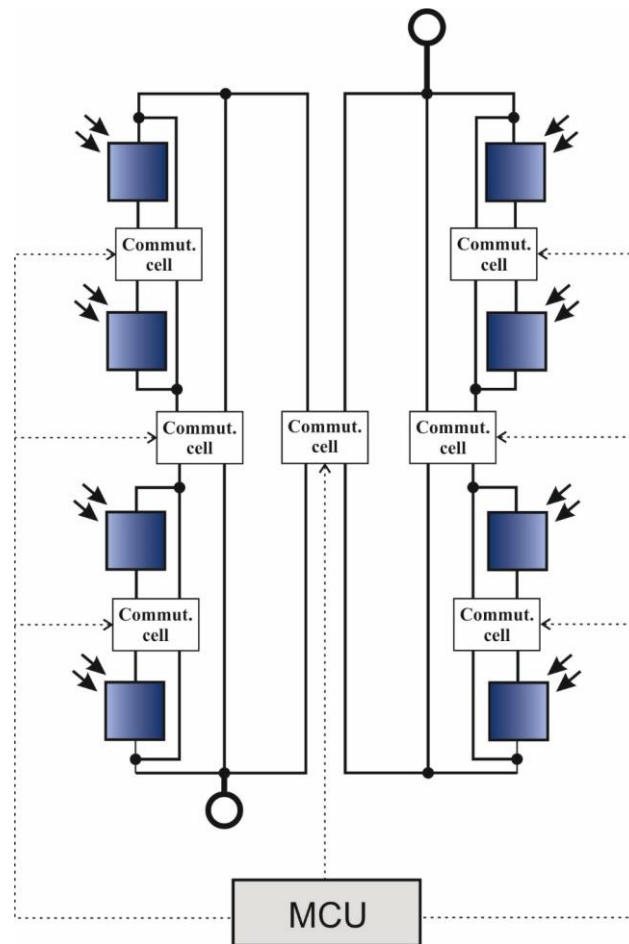


Fig. 3. Connection of PV-cells to sub-strings in a module or panel by commutation cells

It should be noted that by implementing a power source through dynamic topology reconfiguration, a converter-based optimizer—consisting of step-up (boost) and step-down (buck) stages—can be excluded from the design. Furthermore, dynamic commutation, coupled with a specialized algorithm for a programmable controller, enables the realization of inverter functionality. This allows for the generation of an alternating current (AC) output with the

required waveform without the need for an external device [28].

Consequently, to develop a smart power source based on the circuit proposed in Figure 3, it is sufficient to integrate a controller capable of grid monitoring and performing communication and telemetry functions. This integration facilitates the networking of multiple sources into a unified system (Fig. 4).

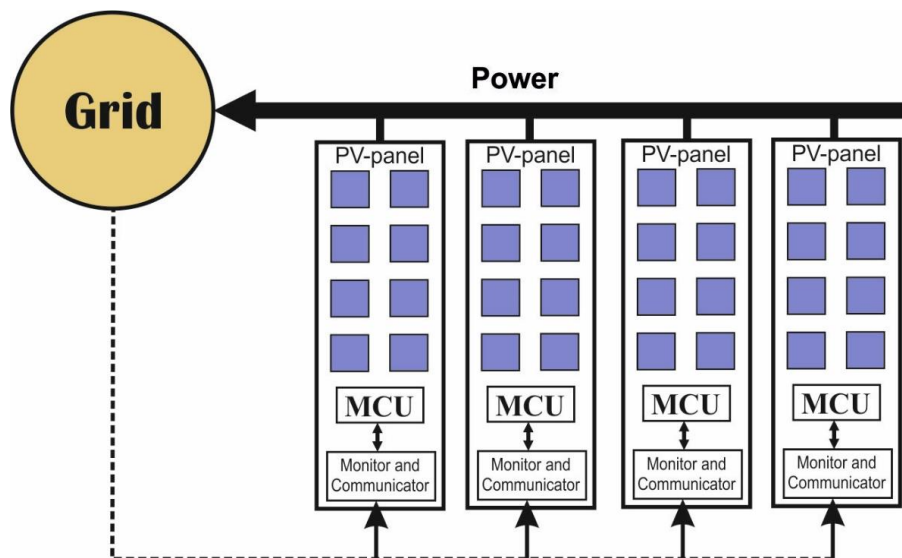


Fig. 4. Integration of multiple sources into a unified smart system

Discussion

The research into the construction of smart photovoltaic sources demonstrates the development of an advanced energy system that utilizes intelligent hardware for dynamic power management. This approach allows sources to operate collaboratively, optimizing performance, extending operational lifespan, and creating modular, adaptive energy solutions for complex environments, such as cluster systems [29].

A significant result of implementing controlled connections is dynamic optimization. Specifically, the system can modify source properties in real time, prioritizing specific output parameters based on the requirements of the application. In one of the implemented circuit solutions, smart source management—achieved by bypassing weaker elements, isolating faulty cells, or redistributing energy—enhances the overall performance of the power system. In another configuration, a universal switching unit (commutation cell) enables dynamic alteration of output parameters without significant energy losses.

The application of an optimal topology [30], utilizing a series-parallel commutation unit, facilitates a wide range of output values and various output signal waveforms. Furthermore, it is essential to emphasize the specific key advantages of smart panels:

1. Efficiency under shading conditions. In conventional systems, if a single panel is shaded (e.g., by a chimney or a tree), the power of the entire string drops to the

level of the weakest link. A smart panel isolates the issue: while the shaded module operates at reduced capacity, all other modules continue to generate maximum power.

2. Granular Monitoring. Real-time production data for each specific panel can be accessed via specialized software. This allows for the immediate detection of malfunctions or soiling on individual modules.
3. Enhanced Safety (Rapid Shutdown). In the event of an emergency or maintenance, smart systems can automatically reduce the voltage of each panel to a safe level, which is critical for the safety of first responders and maintenance personnel [17, 18].
4. Installation Versatility. Since each panel operates independently, they can be installed at different angles and on various roof slopes within a single string.
5. Comprehensive Control. These systems provide precise tracking of the investment's state and deliver notifications regarding any operational anomalies.

Regarding the communication architecture of smart systems, it is proposed that, in accordance with the OSI model [31], the DataLink layer or Network layers of the information network—distributed via dedicated lines or Power Line Communication (PLC) (Fig. 5)—utilize a frame or packet structure containing the address of the controlled device. This enables the integration of a large number of sources into a distributed system with comprehensive data transparency for every node.

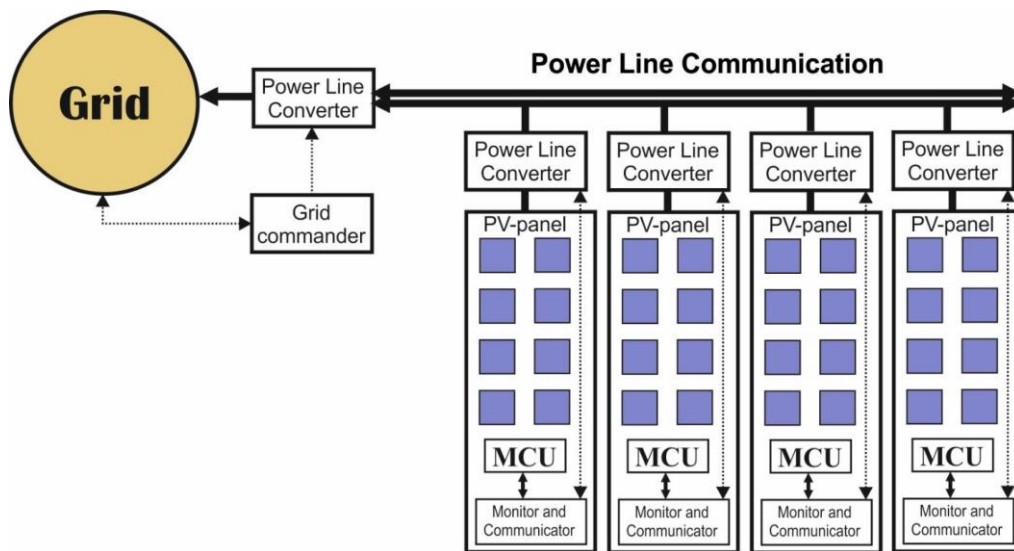


Fig. 5. Integration of multiple sources into a unified smart system by PLC

Furthermore, it is essential to specify that the data exchange protocol between the controllers must encompass commands for reading and writing data from the system components, as well as specific control directives for the power elements. The master controller within the network should issue control commands to the subordinate managed sources. Consequently, by acquiring real-time data and executing system-level control, the master controller

can select operational modes according to a predefined grid management algorithm to ensure optimal system performance and efficiency.

The unification of the logic, address space, and communication protocol establishes a new class of devices: smart photovoltaic units or components. These devices are characterized by their capacity for self-organization and self-monitoring, regardless of the overall system configuration.

Given its versatility and potential, the proposed approach provides a robust framework for the development of both small-scale standalone systems and large-scale grid-tied photovoltaic networks.

Conclusion

Smart photovoltaic sources serve as a pivotal instrument for the implementation of universal and adaptive energy systems. Furthermore, the application of controlled connections represents a promising frontier in scientific research and engineering, facilitating the development of versatile generating units and smart grids.

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