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CONTROL OF A THREE-PHASE HYBRID CONVERTER FOR A PV CHARGING STATION

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Abstract
The typical pairing of a DC/DC boost converter and a DC/AC converter is being suggested to be replaced with a hybrid boost converter (HBC), which attempts to decrease switching phases and switching losses. Designing and testing the control system for a three-phase HBC installed in a PV charging station is the main goal of this study. The three-phase AC grid, the DC system supporting hybrid electric vehicles (HPEVs), and the PV system are all interfaced via the HBC. The control strategy is especially made to track the PV system's maximum power point (MPPT), regulate the voltage on the DC bus, and control the AC voltage or reactive power as needed. Detailed switching of power electronics during a test with the control architecture's, for simulation, MATLAB/SimPowersystems is produced. The simulation results clearly demonstrate that the proposed control technique is practicable. To demonstrate the HBC's control performance, laboratory experiments are also run. The study makes use of a number of indicator terminology, including plug-in hybrid vehicle (PHEV), charging station, maximum power point tracking (MPPT), grid-connected photovoltaic (PV), three-phase hybrid boost converter, and vector control.

1. INTRODUCTION

The increasing popularity of Plug-in Hybrid Electric Vehicles (PHEVs) can be attributed to their positive impact on both the environment and the economy [1]. Forecasts from the U.S. Department of Energy suggest that the United States will witness the sale of more than one million PHEVs in the next decade [2]. Researchers have been exploring the integration of three-phase ac grids with PHEVs through charging stations [3]-[5]. Moreover, various studies have compared different PHEV charger setups and techniques [1], [6]. However, the growing adoption of PHEVs might exert strain on the power grid during charging periods, necessitating the exploration of sustainable solutions. One promising approach involves incorporating Photovoltaic (PV) systems into charging stations as an additional power source [7]. Researchers have proposed architectures and controllers for PV charging stations [7] and developed charging management strategies that consider the grid's loading limit [8]. Yet, many of these systems require controlling multiple power electronic converters for PHEV charging, leading to increased complexity and power losses. Therefore, this paper aims to address this issue by implementing a multi-port converter within a PV charging station for PHEVs and designing an efficient controller.

Related Works

Researchers suggested using inverse Watkins-Johnson technology to power both DC and AC loads, reducing the number of switching stages. Single-phase and three-phase hybrid booster transformers (HBCs) were established in earlier research [10] and [11] for minor grid integration, accommodating DC and AC demands. A single-phase hybrid transformer has been used in grid-connected contexts, according to recent publications [12]. The MPPT function for PV systems in HBCs, however, was not created because earlier research on HBC controller design [10]–[12] required connection to a solid-state DC power source. The synchronization with the vector control function and thorough knowledge of the switching mechanism are necessary for MPPT implementation in HBCs, which is a difficult task.

Our Contributions

In this study, a three-phase hybrid boost converter (HBC) is used to demonstrate a novel method of power management and control at a PV charging station for plug-in hybrid electric vehicles (PHEVs). To effectively charge PHEVs, the proposed charging station combines power from PV arrays and the AC grid. The PV Maximum Power Point Tracking (MPPT) is incorporated into the control architecture, which guarantees proper regulation of the DC voltage for PHEVs.

The study makes two important contributions. A three-phase HBC is used to integrate PV arrays, PHEVs, and the utility grid in the new PV charging station architecture that is first introduced. In comparison to conventional charging stations, this cutting-edge topology reduces the number of power conversion stages and losses. Multiple converters' functions are combined into a single structure by the HBC Secondly, the paper presents the design of the HBC controller with integrated MPPT for the PV system. Unlike existing controllers, which assume a stable DC voltage source, this research implements the MPPT algorithm within the HBC, leading to more efficient power extraction and improved overall performance of the charging station.

2. SOLAR CELL

2.1 Basics of Solar Cells

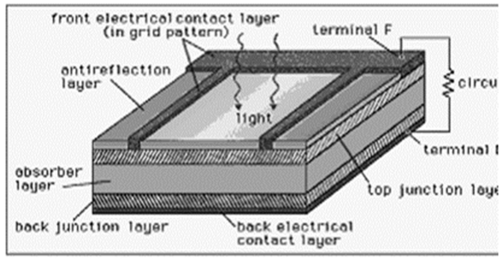


Fig.1 Solar cell

The majority of solar cells are made using silicon, with variations in efficiency and cost based on the type of silicon used, ranging from amorphous to polycrystalline to crystalline forms. Unlike batteries or fuel cells, solar cells don't rely on chemical reactions or fuel; they have no moving parts, unlike electric generators.

Solar cells are designed with multiple layers to efficiently convert light into electricity. Light enters through an antireflection layer, minimizing loss through reflection and transmitting it to the energy-conversion layers below. These layers include the top junction layer, the absorber layer, and the back junction layer. Electrical contact layers carry the current to an external load and complete the circuit. Semiconductor materials like silicon, gallium arsenide, indium phosphide, and copper indium selenite are used in solar cells for efficient light absorption. When light strikes a solar cell, it excites electrons in the absorber layer, creating an electric field that induces the photovoltaic effect. This drives the flow of electrons into an external circuit, enabling useful work. Manufacturing methods and materials impact the efficiency and cost of solar cells. External factors like weather conditions also influence the panel's output, and the goal is to maximize power extraction regardless of weather or cell efficiency.

2.2 Solar Cell Characteristics

It is difficult to pinpoint the maximum power point (MPP) of a solar cell because the properties of the solar cell's current-to-voltage (I-V) and power-to-voltage (P-V) ratios are non-linear. Unlike linear curves, where the MPP is easily found at the midpoint, the MPP on a solar cell's non-linear curve requires more sophisticated methods.

Fig. 1.1 typically displays the I-V characteristic of a solar cell. At the MPP, the solar cell operates with an optimal combination of voltage and current that maximizes power output. This point is critical for achieving the highest efficiency and extracting the most power from the solar cell under given operating conditions.

Due to the non-linear nature of the curve, various techniques are employed to accurately find the MPP. These techniques include Perturb and Observe (P&O), Incremental Conductance, and the Fractional Open Circuit Voltage method. These algorithms are utilized in Maximum Power Point Tracking (MPPT) controllers, which continuously adjust the load to ensure the solar cell operates near its MPP, maintaining efficient power conversion even in varying environmental conditions or load demands. By tracking the MPP, the overall performance and energy harvesting capability of the solar cell are significantly enhanced.

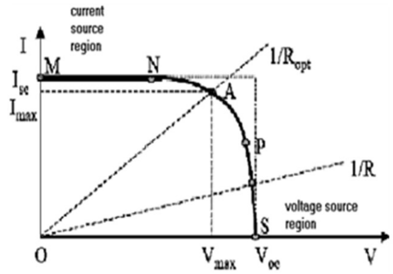


Fig.1.1 Solar cell Characteristics

In a sun based cell, deciding the Greatest Power Point (MPP) is fundamental because of the non-straight connection among current and voltage. The MPP addresses where the result of voltage and result current is at its most elevated, commonly tracked down around the corner or 'knee' of the I-V trademark bend.

The sun powered cell's working trademark comprises of two areas: the ongoing source district and the voltage source area. The ongoing source district is arranged on the left half of the I-V bend, where the interior impedance is high, bringing about the result current excess somewhat consistent notwithstanding varieties in terminal voltage. Then again, the voltage source locale is situated on the right half of the I-V bend, where the inward impedance is low, making the terminal voltage remain moderately stable over an extensive variety of result current. To guarantee productive activity of the sunlight based charger framework, most extreme Power Point Following (MPPT) changes the sun powered charger's result voltage to the ideal worth where greatest energy is conveyed to the heap. Nevertheless, keeping up with the working point at the MPP can be trying because of changing encompassing circumstances, requiring constant following of the power bend.

The expression "irradiance" alludes to how much sunlight based energy arriving at the ground and is normally estimated as 1000 W/m2 at the equator under ideal circumstances. It essentially influences the result of the sunlight based charger as it fills in as the energy asset for the board. Planning PV frameworks includes considering how much sunlight based radiation got at a particular area, considering the tendency point and direction overstretched periods. Sun based radiation unequivocally affects the sunlight based charger's result, as exhibited in Fig 1.2, which outlines the I-V and P-V qualities of a sun-oriented cell under different irradiance levels.

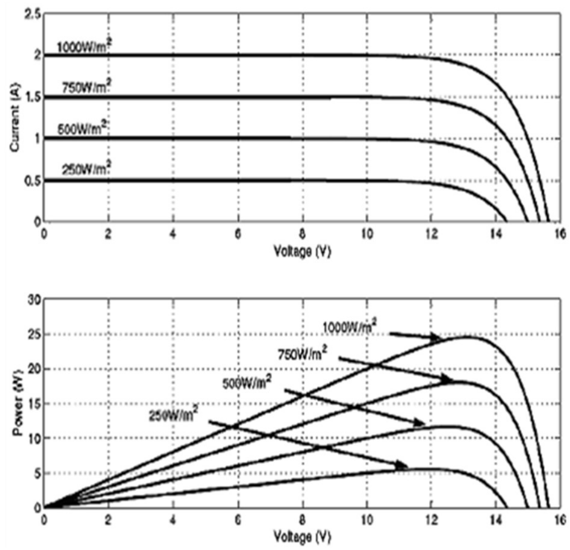


Fig 1.2 I-V and P-V characteristics of a solar cell for various irradiance

The amount of sunlight that solar panels get at a particular place is greatly influenced by their orientation and inclination angles. The orientation is assessed relative to the south in northern latitudes and relative to the north in southern latitudes. The inclination angle, meanwhile, is calculated in relation to the horizontal plane. These factors enable us to determine the quantity of sunlight, or irradiance, that reaches a specific spot, and irradiance data are easily accessible for many locations across the world. As shown in Figure 1.2, the output power of a solar panel is directly proportional to the amount of irradiance it receives. Lower irradiance results in reduced power output, primarily affecting the output current because the generation of current in solar cells relies on the flux of photons. During conditions of low irradiance or dim light, less current is generated due to the decrease in photon flux. Conversely, in bright sunlight or high light intensity, more current is generated because of the increased photon flux.

Variations in irradiance have a negligible impact on voltage and are typically regarded as unimportant in real-world settings. However, temperature is a key factor in forecasting how a solar panel will behave. The I-V (current-voltage) and P-V (power-voltage) characteristics of a solar panel at various temperatures are shown in Figure 1.3 Due to decreased electron and hole mobility in the semiconductor material, mainly silicon, which is frequently used in solar panels, the terminal voltage rises with decreasing temperature. The efficiency of the solar cell can decrease at higher temperatures. Although the higher reference temperatures in Figure 1.3 are not realistic operating conditions, they demonstrate the impact of temperature on the electron and hole mobility, which affects the overall performance of the solar panel. Therefore, both irradiance and temperature should be considered together to make accurate predictions and efficiently design photovoltaic (PV) systems.

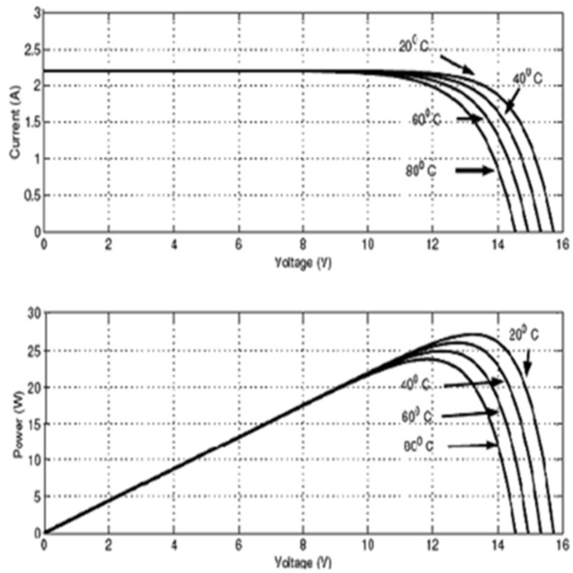


Fig 1.3 I-V and P-V characteristics of a solar cell for varying Temperature

The efficiency of a solar cell is influenced by factors such as irradiance, temperature, inclination, location, and time of the year. These variables affect the amount of sunlight received by the solar panel and its power output. Understanding and accounting for these factors are essential for designing efficient photovoltaic systems that operate optimally at the maximum power point. By tracking this point, the solar cell can achieve peak efficiency, regardless of changing external conditions.

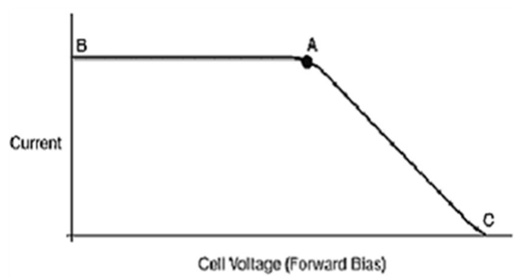


Fig 1.4 Illustration of Maximum power point

To achieve maximum energy transfer from solar cells to the load, operating at point A on the I-V curve is crucial, where the product of voltage and current is maximized. This point represents the maximum power output of the solar cell, ensuring optimal performance. Points B and C, where the short circuit current and open circuit voltage intersect the axes, should be avoided as they do not contribute to energy transfer. Matching load impedance and source impedance in a solar panel array is essential. By grouping solar cells based on their I-V characteristics, each array can operate at its maximum energy transfer point, ensuring efficient power extraction and utilization. However, accurate I-V measurements pose challenges due to the high capacitance associated with solar cell p-n junctions, particularly with larger cell size and junction area, making fast measurements difficult.

The total circuit voltage, which is the voltage across the solar cell, and the incident light intensity together determine the external circuit current, which is the current flowing through the external load connected to the solar cell. In summary, optimizing solar cell performance requires operation at the maximum power point (point A) on the I-V curve and impedance matching in solar panel arrays. Yet, challenges in obtaining fast and accurate I-V measurements stem from the high capacitance of solar cell p-n junctions.

2.3 Solar Cell Modeling

Solar cells operate by utilizing semiconductor materials that respond to light through photon reflection and absorption. This process generates free carriers (electrons and holes) and creates an electric field. The effectiveness of the solar cell process depends on various semiconductor properties, including the absorption coefficient, surface reflectance, drift-diffusion parameters, and surface recombination velocities.

These properties play a vital role in determining how efficiently the solar cell converts incident light into electricity. In practical applications, a single solar cell may not provide sufficient voltage for the desired output, so multiple solar cells are connected in series to form a "Solar Module." These modules are rated at Standard Test Conditions (STC), which include specific conditions such as 1000 W/m2 illumination, Air Mass 1.5 spectrum, and a module temperature of 25°C during testing. Manufacturers' datasheets provide important module parameters, such as the short circuit current (Isc) and open circuit voltage (Voc), which help users understand the module's performance characteristics.

The simplified equivalent circuit model of a solar cell comprises a diode and a parallel current source. The current source generates photocurrent (IPh), which is proportional to the solar irradiance (G), representing the amount of light falling on the solar cell. The p-n transition area of the solar cell is represented by a diode, which allows current to flow in one direction while blocking it in the reverse direction. Understanding these semiconductor properties, the equivalent circuit model, and the key module parameters is essential for accurately modeling the behavior of solar cells and designing efficient solar energy systems. By considering these factors, engineers and researchers can optimize the performance and output of solar cells and create more effective and reliable solar energy solutions.

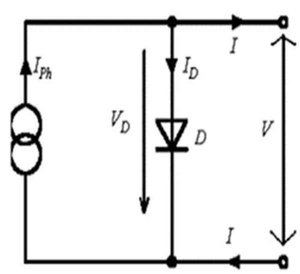


Fig 1.5.Equivalent circuit of solar cell

$I=I_{ph}-I_d=I_{ph}-I_s.(\exp(v/m.V_T)-1$ **… (2.1)**

Where

Iph- Photo current

ID - Diode current
Ig- Diode reverse saturation current
m -Diode ideal factor

V_T-(k*T)/q is Thermal voltage (25.7 mV at 25°C)

k = Boltzmann Constant=1.3824*e-23
T= Absolute Temperatures
q=charge of an electron-1.60e-19 coulomb's
V = output voltage of the solar cell
I = output current through the solar cells
It's possible that not all of the electrical functions of a solar cell are covered by the earlier simplified equivalent circuit. Voltage losses along the path to the exterior contacts, which must be taken into account in real solar cells, can be simulated by adding a series resistor RS to the equivalent circuit. Leakage currents may also happen and this phenomenon can be represented by a parallel resistor RP (as seen in Fig. 1.7). These extra components provide a more thorough depiction of the electrical behavior and performance of a solar cell, allowing for more accurate modeling and comprehension of the numerous losses and inefficiencies that may happen under actual conditions. Derived from Kirchhoff's first law the equation for the extended I-V curve could be achieved.

$I = Iph - I_D - Ip$ (2.2)

$p = V_d / Rp = [(V + IR s)]/Rp$ (2.3)

$I = Iph - \{I_s(\exp(q(V+IRs)/mkTNs)-1\} - (V+IRS / Rp)$ (2.4)

Where

I_{PR} is the photo current

$I_{\{D\}}$ is the Diode current

R_{x} is the cell's series resistance, R{p} is the shunt resistance

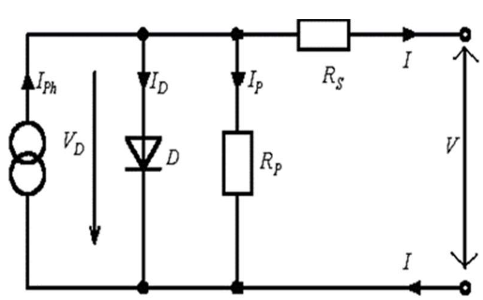


Fig1.6 Equivalent Circuit for One Diode Model for Solar Cell

Table 1: The key specifications of the solar MSX - 60 PV panel

At Temperature T = 25°C, Insulation G-1000W/m²		
Open circuit Voltage	V_{sc}	21.0V
Short circuit Current	I_{sc}	3.74A
Voltage at max.power	V_m	17.1V
Current at max.power	I_m	3.5A
Maximum power	P_m	60.0W

3. PHASE LOCKED LOOP

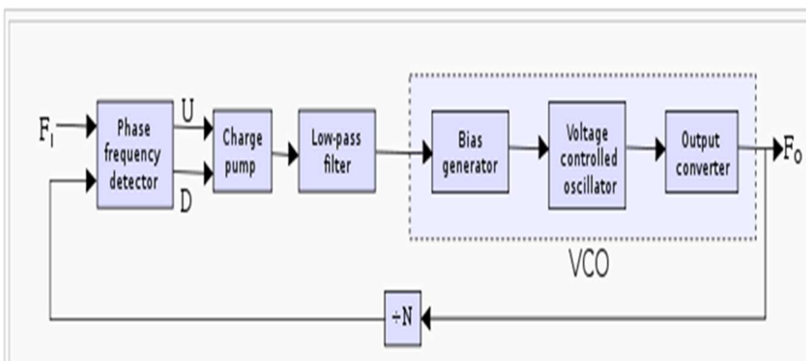


Fig.1.7 Phase Locked Loop

A Phase-Locked Loop (PLL) is a control system that generates an output signal with a phase related to an input reference signal. It consists of a variable frequency oscillator and a phase detector, which compares the phases of the oscillator's output and the input signal. The phase detector's output adjusts the oscillator's frequency, maintaining phase alignment in a feedback loop. PLLs ensure coordination of input and output frequencies, beneficial for frequency synthesis and demodulation. For reliable frequency production, signal recovery, and clock distribution in radio, telecommunications, computers, and electronic devices. PLL is widely used in contemporary electronics across a number of frequency bands because integrated circuits provide all the necessary building pieces.

Communication, signal processing, and frequency synthesis are just a few of the many applications that make use of the Phase-Locked Loop (PLL), a fundamental electronic control system. Phase and frequency synchronization between an output signal and an input reference signal is its main purpose. PLLs are a necessity in contemporary electronics because of their capacity to preserve this phase coherence, where exact timing and synchronization are essential.

Applications:

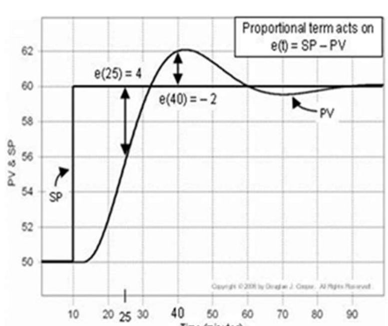
Phase-locked loops (PLLs) find a wide range of applications in various fields due to their ability to synchronize and stabilize signals. Some common applications include:

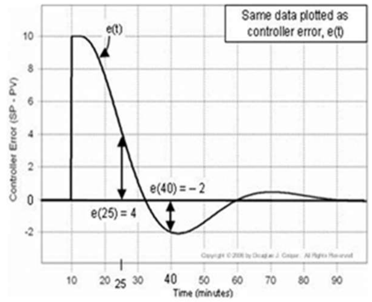
1. Space Communications: PLLs are used for coherent demodulation of signals in space communications to extract the original information accurately.
2. Radio Communications: PLLs are used for bit synchronization and symbol synchronization in radio receivers to recover transmitted data.
3. Frequency Demodulation: PLLs can be used to demodulate frequency-modulated (FM) and amplitude-modulated (AM) signals.
4. Lock-In Amplifiers: PLLs can recover small signals buried in noise, making them useful in applications like signal processing and scientific measurements.
5. Clock Recovery: PLLs can extract clock timing information from data streams, which is useful in various digital communication and data storage systems.
6. Frequency Synthesis: PLLs are used to generate new frequencies that are multiples of a reference frequency, providing precise and stable clock signals for various applications.
7. DTMF Decoders: PLLs are used in telecommunication systems to decode dual-tone multi-frequency (DTMF) tones for remote control applications.
8. Modems: PLLs are used in modems for data communication, ensuring accurate timing and synchronization.

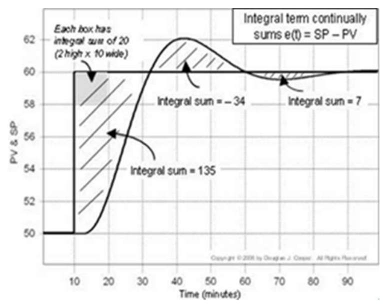
Advantages and disadvantages

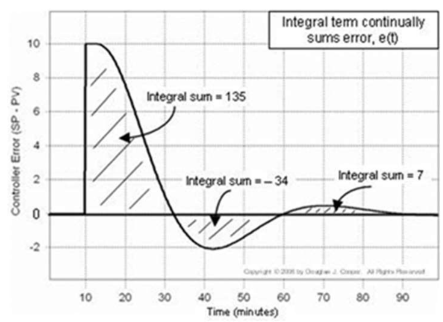
- The integral term in a Proportional-Integral (PI) controller plays a crucial role in reducing steady-state error to zero. In contrast, a proportional-only control lacks this capability, and steady-state error may persist.
- Omitting the derivative action in a control system can improve its steadiness in the presence of noisy data. This is because the derivative action is more sensitive to high-frequency components in the inputs, which can amplify noise.
- A PI-controlled system, without derivative action, may exhibit less responsiveness to rapid and significant changes in the system's state. Consequently, it could take longer to reach the desired set point and may respond more slowly to disturbances compared to a well-tuned Proportional-Integral-Derivative (PID) system.

4. RESULTS

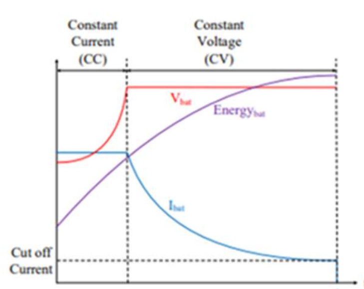








The integral of each shaded area has the same sign as the mistake, which is a crucial distinction to make. When the controller is first switched to automatic mode, the integral sum begins to build up. As long as e(t) is positive, the integral sum total increases, and when it is negative, it decreases. The integral sum is 135 - 34 = 101 at time t = 60 minutes on the plots, representing the accumulated positive mistakes up to that point. At t = 90 min, when the reaction has stabilized, the integral sum is 135 - 34 + 7 = 108, suggesting that positive errors are still accumulating but at a slower rate. This behaviour of the integral term in the PI controller allows it to maintain a memory of past errors, adjusting the control action to compensate for any accumulated deviations from the set point, contributing to the stability and precision of the control process.



5. CONCLUSION

In this study, a three-phase hybrid boost converter (HBC) control system for a solar charging station is presented. To cut down on switching losses, HBC combines a DC/DC booster and a DC/AC converter into a single converter construction. Maximum power point tracking (MPPT), DC voltage management, and reactive power tracking are the three main goals of this control system. The control system employs a modified incremental conductivity PI-based MPPT technique to produce MPPT in order to effectively track the PV array's maximum power production.

DC voltage control and reactive power tracking employ vector control techniques. With the use of these procedures, AC currents can be precisely controlled, and DC voltage may be regulated, resulting in stable operation and effective power conversion. The performance of the proposed control system is evaluated through computer simulations and experimental tests. Five case studies demonstrate the effectiveness of MPPT, DC voltage control, reactive power tracking, and overall power management of a PV charging station.

Results from simulations and experiments confirm that the HBC topology-based PV charging station operates successfully. The suggested control system ensures a consistent and dependable DC power supply by making the best possible use of both PV electricity and AC grid power. Professor who made contributions to the creation and enhancement of the suggested control system. The authors like to thank Ling ling Fan for his insightful remarks and ideas. The collaborative nature of the research and the assistance provided during its completion are highlighted in the acknowledgments.

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