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INTEGRATION OF SOLAR PV SYSTEMS INTO A THREE-PHASE DISTRIBUTION FEEDER USING AN ADAPTIVE P&O TECHNIQUE

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Abstract:

To maximize power extraction from a double-stage solar photovoltaic energy conversion system (SPVECS) connected to a three-phase distribution grid, this study proposes an enhanced perturb and observe algorithm with adaptive perturbation size (IAP&O). The conventional P&O technique remains the most widely adopted Maximum Power Point Tracking (MPPT) method in residential and commercial sectors due to its simplicity. However, its efficiency is compromised by the drift phenomenon, particularly under rapidly changing environmental conditions.

In this double-stage SPVECS, a Voltage Source Inverter (VSI) is integrated with the three-phase distribution grid, ensuring compliance with power quality standards, especially concerning harmonic distortion. This configuration effectively maintains sinusoidal grid currents and facilitates the delivery of real power to the distribution network. The system's performance is evaluated through simulations conducted in MATLAB/SIMULINK, demonstrating the effectiveness of the proposed approach.

INTRODUCTION

Over the past few decades, solar photovoltaic (SPV) power conversion has emerged as a prominent alternative among renewable energy sources. Despite its advantages, like other renewable energy technologies, it presents both benefits and challenges, including ease of deployment, modularity, long lifespan, quick installation, variability, cost, space requirements, and power quality issues. The performance of a solar photovoltaic energy conversion system (SPVECS) is highly dependent on changing environmental conditions, as the relationship between the PV array's voltage and current is inherently non-linear. Consequently, there exists a unique operating point where the solar PV array delivers maximum power, known as the Maximum Power Point (MPP).

The efficiency of any SPVECS significantly relies on the effectiveness of the Maximum Power Point Tracking (MPPT) algorithm. Over time, numerous MPPT techniques have been introduced to enhance PV system performance. In the existing literature, popular MPPT methods include Hill Climbing, Perturb and Observe (P&O), Incremental Conductance, Neural Networks, Particle Swarm Optimization, Sliding Mode Control, Ripple Correlation Control, and Incremental Resistance (IR) techniques. Additionally, recent advancements have explored bio-inspired algorithms, such as Artificial Bee Colony (ABC) and Firefly Algorithms.

Despite the development of advanced MPPT strategies, the P&O algorithm remains widely adopted due to its simplicity, ease of implementation, and real-time applicability in both analog and digital systems. The P&O algorithm operates based on the slope of the power-voltage (dP_{pv}/dV_{pv}) characteristic of the PV module. To the left of the MPP, the slope is positive, while it becomes negative to the right of the MPP. The perturbation direction of the operating voltage is determined based on the slope's sign to continuously track the maximum power output.

Implementation schemes for the P&O algorithm generally involve controlling either the reference voltage through a Proportional-Integral (PI) controller or the duty cycle of the converter. The tracking performance of the P&O method is influenced by factors such as tracking speed and steady-state oscillations, both of which are highly sensitive to the perturbation step size. A smaller step size results in lower oscillations but slower response times, while a larger step size enhances response speed but introduces significant steady-state oscillations. To address this trade-off and optimize the P&O algorithm's performance, an adaptive approach to perturbation size is essential.

Although the P&O method offers several advantages, it faces limitations, particularly under rapidly changing climatic conditions, where it may deviate from the MPP. This study presents an analysis of the MPP deviation, explores the underlying causes, and proposes solutions to mitigate these issues. Specifically, it introduces an adaptive perturbation size technique that incorporates current variations to enhance the traditional MPPT method's efficiency.

Furthermore, due to the intermittent nature of solar power generation, direct load feeding is often impractical, necessitating the integration of energy storage systems. However, such solutions are neither cost-effective nor feasible on a large scale. A more practical alternative is the development of grid-connected SPV systems. When interfacing solar power with the utility grid, it is crucial to maintain power quality standards to ensure that the integration of renewable energy does not adversely affect the stability and reliability of the distribution network.

Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is a technique widely used in renewable energy systems such as wind turbines and photovoltaic (PV) solar systems to optimize the extraction of power under varying environmental conditions. Although solar power is primarily addressed, this method is applicable to all power sources with variable output, including optical power transmission and thermophotovoltaics.

PV solar systems are configured in various ways in relation to inverters, external grids, battery banks, and other electrical loads. Regardless of the destination of the solar power, the key issue that MPPT addresses is that the efficiency of power transfer from the solar cells depends on both the intensity of sunlight and the electrical characteristics of the load. As sunlight varies, the load characteristics that yield the highest power transfer efficiency also change, so the system's performance is optimized by adjusting the load characteristics to maintain maximum efficiency. This optimal load characteristic is called the maximum power point (MPP), and MPPT aims to locate and maintain this point.

Electrical circuits can be designed to provide various loads to the photovoltaic cells, converting voltage, current, or frequency to match different devices or systems. MPPT solves the challenge of selecting the ideal load for the solar cells to extract the most usable power.

Solar cells exhibit a complex relationship between temperature and total resistance, resulting in a non-linear output efficiency that can be analyzed through the I-V curve. The MPPT system samples the output of the PV cells and adjusts the load to maximize power under varying environmental conditions. MPPT devices are generally integrated into power converter systems that provide voltage or current conversion, filtering, and regulation for diverse loads such as power grids, batteries, or motors.

I-V Curve: Fig. 1.1: Photovoltaic solar cell I-V curves, where the line intersects the curve at the knee, representing the maximum power transfer point.

MPPT in Solar Inverters: Solar inverters convert DC power to AC power and often incorporate MPPT. These inverters monitor the output power (I-V curve) from the solar modules and apply the appropriate load resistance to achieve maximum power.

The power at the MPP (Pmpp) is the product of the MPP voltage (Vmpp) and MPP current (Impp).

MPPT Implementation: When a load is directly connected to the solar panel, the operating point of the panel rarely coincides with the peak power. The impedance seen by the panel determines the operating point, and by varying the impedance, the operating point can be adjusted towards the peak power point. Since solar panels are DC devices, DC-DC converters are used to adjust the impedance of the circuit. Changing the duty cycle of the DC-DC converter alters the impedance, and at a specific duty cycle (or impedance), the operating point reaches the peak power transfer point.

The I-V curve of the panel changes with variations in atmospheric conditions such as radiation and temperature, so it is not feasible to set the duty cycle statically. MPPT implementations use algorithms to sample panel voltages and currents periodically and adjust the duty cycle as necessary. Microcontrollers are often employed to implement these algorithms, with modern implementations utilizing large computers for analytics and load forecasting.

MPPT Techniques Classification: Several strategies can be employed to optimize the power output of a PV array. Maximum power point trackers may use different algorithms and switch between them based on the array's operating conditions.

1. **Perturb and Observe (P&O)**: In this method, the controller adjusts the voltage by a small amount and measures the resulting power. If power increases, the adjustments continue in that direction until no further increase is detected. This method is widely used due to its simplicity, although it can cause oscillations in power output. P&O is considered a hill-climbing technique, as it follows the slope of the power-voltage curve.

A) **Incremental Conductance (IncCond)**: This method measures incremental changes in PV array current and voltage to predict the impact of voltage changes. While more computationally intensive than P&O, IncCond can track changing conditions faster. Like P&O, it may lead to oscillations. IncCond compares the incremental conductance (dI/dV) to the array conductance (I/V), with the maximum power point occurring when these values match.

Current Sweep: This method involves using a sweep waveform for PV array current to obtain and update the I-V curve at fixed intervals, after which the maximum power point voltage is computed from the curve.

Constant Voltage: In the constant voltage method, the output voltage is maintained at a constant value under all conditions, or adjusted based on a ratio to the open-circuit voltage (VOC). This approach does not strictly track the maximum power point, but it may be used as a backup when MPPT methods fail.

Comparison of Methods: Both P&O and Incremental Conductance are "hill-climbing" methods that aim to find the local maximum of the power curve under the given operating conditions.

- **P&O**: May cause oscillations around the maximum power point even under steady-state conditions.
- **Incremental Conductance**: Offers the advantage of more accurately finding the maximum power point without oscillations, especially under rapidly changing atmospheric conditions. However, it can still cause oscillations and may require higher sampling frequencies.

MPPT Placement: Traditional solar inverters perform MPPT for the entire PV array. In such systems, the same current flows through all modules, which can result in lower performance if some modules perform below their MPP due to shading or other factors. Some companies now implement MPPT at the individual module level, allowing each module to operate at peak performance regardless of shading or mismatches.

Operation with Batteries: In off-grid PV systems, batteries can supply power at night. MPPT helps resolve the mismatch between the battery voltage and the PV panel's maximum power point voltage, especially at sunrise when the battery has been partially discharged. When excess power is generated and there is no load to absorb it, MPPT adjusts the PV operating point to match production with demand. Alternatively, excess power can be diverted into a resistive load, as often done in spacecraft.

In grid-connected PV systems, MPPT ensures that all power generated by the solar panels is fed into the grid, keeping the PV system at its maximum power point.

Photovoltaic (PV) Systems: Photovoltaics is the conversion of light into electricity using semiconducting materials that exhibit the photovoltaic effect. PV systems can be ground-mounted, roof-mounted, or wall-mounted, with either fixed mounts or solar trackers to follow the sun. Photovoltaic systems generate no pollution during operation and require no moving parts. However, their efficiency depends on sunlight, and their output is reduced if tracking systems or other mitigating factors like dust or cloud cover are not used. Advances in technology and increased manufacturing have reduced costs and improved reliability and efficiency.

Despite these challenges, PV systems are increasingly being adopted worldwide, supported by economic incentives and government programs aimed at reducing the cost of solar energy.

CONVERTERS

The term "converters" refers to devices designed to transform electrical energy from one form to another. This transformation can involve converting alternating current (AC) to direct current (DC) or vice versa. The process of converting AC to DC is known as **rectification**, while the conversion of DC to AC is termed **inversion**.

Power conversion systems can be classified based on the nature of their input and output as follows:

- AC to DC Conversion (Rectifiers)
- DC to AC Conversion (Inverters)
- DC to DC Conversion (DC-DC Converters)
- AC to AC Conversion (AC-AC Converters)

SYSTEM CONFIGURATION

The proposed topology of the Solar Photovoltaic Energy Conversion System (SPVECS) integrated with a three-phase distribution network is illustrated in Fig. 3.1. In this configuration, the PV array is constructed by combining multiple PV strings to facilitate solar power generation. A Voltage Source Inverter (VSI) is employed to deliver active power to the grid, while interfacing inductors are incorporated to mitigate switching current ripples. Additionally, a ripple filter is utilized to suppress switching-induced voltage ripples at the Point of Common Coupling (PCC).

For a PV array with a total capacity of 30 kW, the system comprises 27 modules connected in series and 6 modules connected in parallel. Each PV module is rated at 200.143 W, with a maximum power voltage (Vmp) of 26.3 V and a maximum power current (Imp) of 7.61 A.

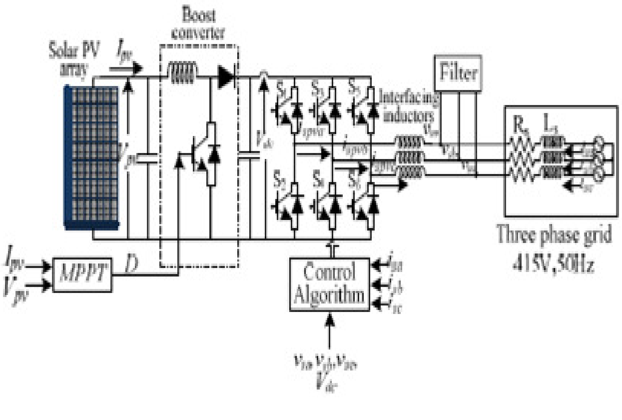


Fig 1 Block diagram of SPVECS

CONTROL TECHNIQUE

The block diagram illustrating the control strategy of the proposed topology is presented in Fig. 3.2. The control system is divided into two main components:

1. **Maximum Power Point (MPP) Control Block**, and
2. **Voltage Source Inverter (VSI) Control Block**.

The Maximum Power Point Tracking (MPPT) algorithm is employed to ensure the SPVECS operates at its MPP by regulating the duty cycle of a DC-DC boost converter. Following this, the VSI current control mechanism is implemented, which serves multiple functions such as improving the power factor (PFC) and mitigating harmonics while delivering active power to the three-phase distribution feeder. The VSI control is designed to operate in a manner that ensures grid stability and compliance with power quality standards.

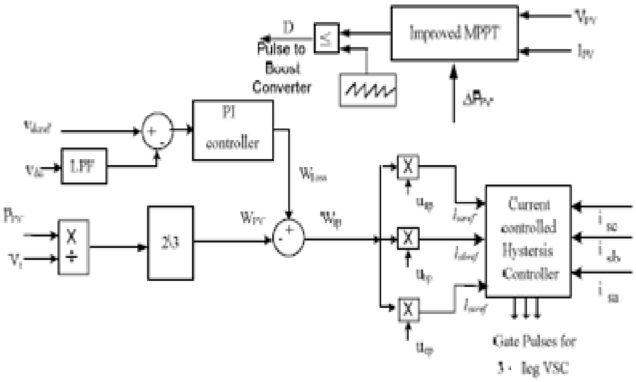


Fig 4.2 Block diagram of Control Architecture for VSI

Improved Perturb and Observe Algorithm with Adaptive Perturbation

In the conventional Perturb and Observe (P&O) control method, the duty cycle is generated by comparing the output with a sawtooth waveform, and it is adjusted to track the Maximum Power Point (MPP) on the power-voltage (P-V) curve of the solar photovoltaic (PV) power conversion system. In this Maximum Power Point Tracking (MPPT) strategy, the PV voltage and current are measured at each iteration to calculate the corresponding power. If the product of PV power and voltage in the current iteration is greater than that of the previous iteration, the PV voltage is increased, and the new value is updated.

Conversely, if the product is lower, the PV voltage is decreased, and the updated value is applied.

The simplicity of real-time implementation and effective tracking performance make the P&O MPPT technique one of the most widely adopted methods. Its primary advantage lies in its fast convergence speed, which can be achieved in both analog and digital systems. However, this method has notable limitations, such as the **drift problem** and the trade-off between large and small perturbation step sizes. Specifically, during sudden changes in solar irradiance, the conventional P&O algorithm struggles to determine whether the variation in power is due to changes in irradiance or perturbation.

To address these issues, an improved P&O MPPT algorithm has been developed by incorporating the variation in current (ΔIPV) alongside variations in voltage (ΔVPV) and power (ΔPPV). This enhancement helps mitigate the drift problem and introduces an adaptive perturbation step size, reducing steady-state oscillations, as illustrated in Fig. 3.3.

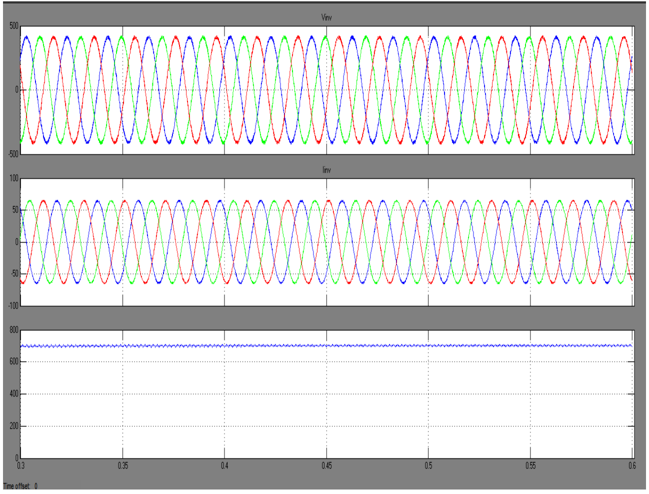
The drift issue arises because the MPPT algorithm cannot accurately identify whether the increase in power is due to perturbation adjustments or changes in irradiance. For example, if there is a sudden increase in irradiance causing the operating point to shift from point 1 to point 4, we observe that ΔPPV = PPV4(kT) - PPV2((k-1)T) > 0 and ΔVPV = VPV4(kT) - VPV2((k-1)T) > 0. In such cases, the duty cycle decreases, causing the operating point to shift away from the MPP (point 5).

To resolve this issue, current variation data (ΔIPV) should also be integrated into the decision-making process. If ΔIPV = IPV4(kT) - IPV2((k-1)T) > 0, along with ΔPPV > 0 and ΔVPV > 0, it can be confidently concluded that the power increase is due to changes in irradiance rather than perturbation.

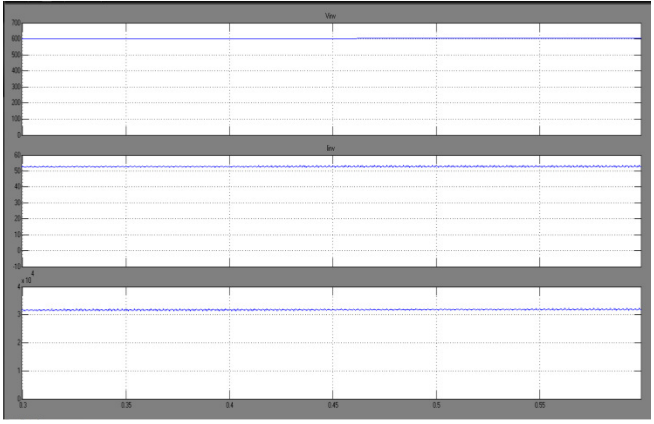
While the P&O method is simple and efficient, it faces challenges related to the drift problem when solar irradiance varies suddenly due to factors such as cloud cover or abrupt weather changes. This issue occurs because, at the moment of sudden irradiance fluctuation, the P&O algorithm cannot accurately judge whether the change in solar power is due to irradiance variation or perturbation. Fig. 4 illustrates the improved P&O approach, which incorporates solar current variation (ΔIPV) alongside voltage (ΔVPV) and power variations (ΔPPV) to enhance tracking performance.

SIMULATION RESULTS

Steady State Behaviour of Proposed System at Constant Insulation

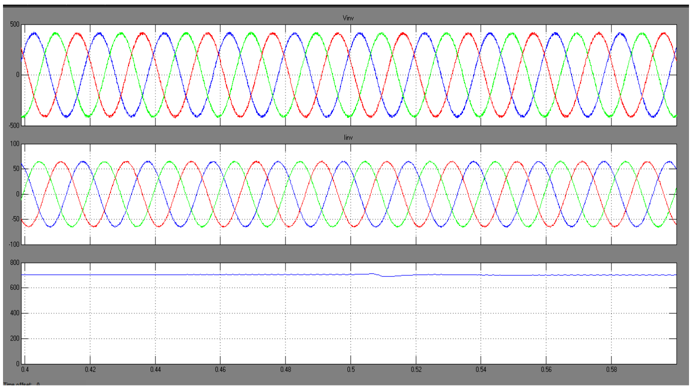


Grid voltages (Vsabc), grid currents (isabc),VSI DC link voltage (Vdc),

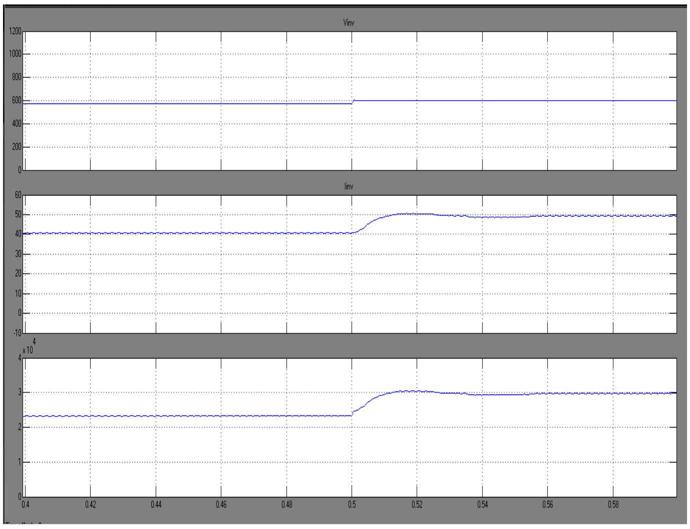


PV array voltage (Vpv), PV array current (Ipv), PV array power (Ppv)

Dynamic behaviour under varying insulation condition



Grid voltages (Vsabc), gridcurrents (isabc),VSI DC link voltage (Vdc)



PV array voltage(Vpv), PV array current (Ipv), PV array power(Ppv)

CONCLUSION

The proposed Maximum Power Point Tracking (MPPT) algorithm has been effectively implemented for interfacing the solar Photovoltaic Energy Conversion System (SPVECS) with a three-phase distribution feeder, successfully demonstrated on a laboratory prototype. This scheme efficiently generates gating pulses for the boost converter, maintains a stable DC link voltage, produces reference currents using unit templates extracted from Point of Common Coupling (PCC) voltages, maximizes power extraction from the SPVECS, and facilitates seamless power transfer to the three-phase grid.

Experimental results indicate that the system successfully delivers maximum power to the grid, with the Total Harmonic Distortion (THD) of the grid current remaining within acceptable limits [15]. The performance analysis confirms that the proposed MPPT algorithm outperforms conventional methods, offering superior steady-state response characteristics.

Additionally, the system demonstrates faster MPPT tracking compared to traditional algorithms. The proposed topology enhances the overall efficiency of the SPVECS by extracting more power with reduced oscillations during steady-state conditions when compared to the conventional Perturb and Observe (P&O) method. Over the entire lifespan of the solar PV array, the implementation of this Improved P&O (IP&O) algorithm enables significant energy gains, maximizing the system's long-term efficiency.

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