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High Gain DC Boost Converter with Enhanced P&O MPPT for Solar Photovoltaic Applications

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Abstract:

In microgrids, distributed generators that cannot be dispatched, such as a photovoltaic system, need to control their output power at the maximum power point. The fluctuation of their output power should be minimized with the support of the maximum power point tracking algorithm under the variation of ambient conditions. This paper presents the design and implementation of a high gain DC boost converter (HGDC-Boost Converter) with an improved perturb and observe maximum power point tracking algorithm for photovoltaic applications. The proposed converter achieves a high step-up ratio, reaching a voltage gain of 10, while maintaining high efficiency and low component count. Compared to traditional methods, the enhanced perturb and observe algorithm provides faster dynamic response and reduced power oscillations around the maximum power point under rapidly changing environmental conditions. To validate the performance of the proposed converter and MPPT algorithm, simulations results are provided, demonstrating the effectiveness of the proposed solution for photovoltaic systems.

Keywords: Renewable energy sources, HGDC-Boost Converter, Maximum power point tracking, Solar Photovoltaic systems & Perturb and Observe algorithm.

I. INTRODUCTION

Renewable energy (RE) is an essential component in meeting the ever-increasing demand of the power system. Among the renewable energy resources (RES), photovoltaic (PV) systems are of the utmost significance for a variety of reasons, including (a) the fact that they produce clean energy, (b) the fact that they are easy to access, and (c) the fact that they offer a significant return on investment in comparison to fossil fuel energy [1]. The ongoing electrification of the automotive sector is significantly elevating the challenges and expectations placed upon power electronics systems. The research is concentrating on alleviating concerns related to range, cost, and charging time to enhance the affordability of electrified vehicles (EVs) for a broader audience. In an all-electric vehicle, the battery cell serves as the sole repository for electrical energy, which in turn powers the propulsion motor [2]. In order to enhance the driving range and diminish reliance on grid-based charging, solar cells are incorporated into the structure of electric vehicles.

The photovoltaic (PV) system is regarded as the most viable technology when compared to other renewable energy sources. The absence of rotating components, negligible ongoing costs, lack of fuel requirements, environmentally friendly characteristics, and abundant availability are significant advantages [3]. The electric characteristics of the P-V and I-V curves of the photovoltaic system exhibit non-linear behavior, which is contingent upon the levels of solar insolation and temperature [4]. Furthermore, to ensure dependable operational performance of the photovoltaic system amidst varying environmental conditions, the inclusion of a battery backup emerges as a critical component. This system effectively stores excess energy during peak generation periods and subsequently delivers this stored energy during peak load scenarios [5]. Nonetheless, the behavior of the photovoltaic system is fundamentally influenced by the photovoltaic charging procedure, which operates at maximum power point (MPP) and produces photovoltaic power that can be delivered to the load. The theorem of maximum power; transfer this principle of maximum power transfer is applicable solely when the internal resistances are matched to the load resistance. Consequently, the implementation of maximum power point tracking (MPPT) is essential to address the non-linear characteristics of the photovoltaic (PV) system and to facilitate the optimal injection of PV power into the load via a DC-DC converter. The regulation of the duty ratio is achieved through the implementation of maximum power point tracking (MPPT) algorithms [6].

The structure of the paper is as follows. The high gain PV architecture under consideration is elaborated upon in Section 2. Section 3 delineates the design process, mathematical modeling, and parameterization, alongside an improved and enhanced P&O MPPT algorithm. Section 4 delineates a high gain DC–DC converter topology along with its control mechanisms pertinent to its operational modes. Section 5 presents a detailed discussion of the simulation results under various climatic conditions. Section 6 presents the concluding remarks of the paper along with potential future directions for research.

II. DESIGNING THE ARCHITECTURE OF PROPOSED APPROACH

This research employs a comprehensive methodology to design a solar power optimizer for high-gain photovoltaic systems, focusing on maximizing energy harvest and system efficiency. The approach encompasses theoretical analysis, simulation modeling, and experimental validation to ensure the robustness and practicality of the proposed solution. Initially, a detailed mathematical model of the PV system, including the PV array, DC-DC converter, and MPPT algorithm, will be developed. This model will serve as the foundation for analyzing system behavior under various operating conditions and for optimizing design parameters. The design of the high-gain DC-DC converter is crucial for efficiently stepping up the low voltage output of the PV modules to a higher voltage level suitable for grid integration or battery charging. Different converter topologies will be evaluated based on their voltage gain, efficiency, component count, and complexity. The selected topology will be thoroughly analyzed and optimized to achieve the desired performance characteristics.

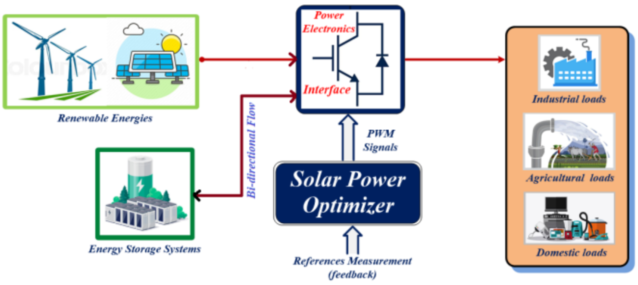

Fig. 1 Proposed approach for HGDC Boost converter in solar PV system with BESS.

Above figure shows the schematic illustration of the ongoing work with P&O MPPT algorithm implemented to ensure optimal power extraction from the PV array under varying environmental conditions. The performance of the MPPT algorithm will be evaluated through simulations and compared with existing techniques. Finally, an experimental prototype of the solar power optimizer will be built and tested to validate the simulation results and demonstrate the effectiveness of the proposed solution in a real-world scenario.

III. DESIGN OF MAIN COMPONENTS

PV modeling and characteristics

The electrical output of the photovoltaic (PV) cell is determined by its current-voltage (I-V) characteristics, which may be correlated with the material properties of the semiconductor.

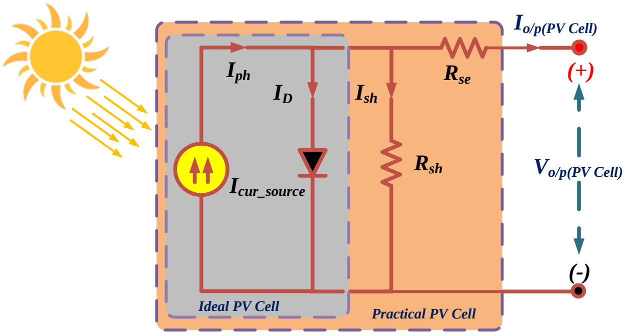

Fig.1 Equivalent circuit of single diode PV module.

The I-V characteristics of a solar cell may be determined by constructing an equivalent circuit of the device, as seen in figure 2. The generation of current I_{ph} by light is represented by a current generator in parallel with a diode which represents the p-n junction. The output current I_c is then equal to the difference between the light generated current I_{ph} and the diode current I_d. In practice, solar cells do not operate under standard conditions. The two most important aspects to be accounted for are the effects due to variable temperature and irradiance. Usually, the PV cells in a module are interconnected in series. The number of cells in a module is governed by the voltage of the module [7]. The three most important electrical characteristics of a module are the short circuit current, open circuit voltage and the maximum power point as function of temperature and irradiance. To simulate PV array, the mathematical model neglecting shunt resistance R_{sh} is used according to the following set of equations:

The output voltage of PV cell is a function of photo current and it depends upon solar insolation level.

$$V_c = \frac{AkT_c}{e}\ln\left(\frac{I_{ph}+I_d-I_c}{I_d}\right)-R_{se}I_c \qquad (1)$$

where, I_c and V_c: cell output current and voltage, respectively; I_d: reverse saturation current of the diode; T_c: cell temperature at standard test conditions (STC) in 0C; k: Boltzmann's constant in J/°C; e: electron charge; I_{ph}: light-generated current; A=1.92: ideality factor; Rse: series resistance. The array voltage is obtained by multiplying equation (1) by the number of the cells connected in series, N_s. The array current is obtained by multiplying the cell current by the number of the cells connected in parallel, N_p. This value of current is valid for a certain cell operating temperature T_c and its corresponding solar insolation level S_c. A method to include the effects of the changes in temperature and solar insolation levels. According to this, a model is obtained for known temperature (T_a) and solar insolation (Sa). The solar cell operating temperature varies as a function of solar insolation level and ambient temperature. The cell output voltage and cell photocurrent are affected by ambient temperature.

Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracking (MPPT) is a critical technology employed in photovoltaic (PV) systems to optimize energy harvesting and enhance overall efficiency. As sunlight intensity and environmental conditions fluctuate, the performance of PV systems can be significantly improved by dynamically adjusting the operating point of the solar modules. This section delves into the principles, significance, and techniques of Maximum Power Point Tracking.

The primary goal of MPPT is to ensure that a PV system operates at its maximum power point, where the solar modules generate the highest amount of electric power under prevailing conditions [8]. Given the variability in sunlight intensity and temperature, MPPT becomes essential for extracting the optimum energy output from solar panels, thus maximizing the overall energy yield of the system.

The efficiency of a PV system is highly sensitive to the operating point of the solar modules. The voltage and current at which the modules produce maximum power vary with environmental factors[9]. MPPT algorithms continuously monitor the electrical characteristics of the modules and adjust the operating point to ensure maximum power extraction. Common MPPT techniques include:

a. *Perturb and Observe (P&O):* This algorithm incrementally adjusts the operating point and observes the resulting change in power. When a decrease in power is detected, the algorithm adjusts the operating point in the opposite direction. This process is repeated until the maximum power point is reached.

b. *Incremental Conductance:* This method calculates the derivative of the power-voltage curve and adjusts the operating point to maintain the slope at zero, indicating the maximum power point.

c. *Fractional Open-Circuit Voltage (FOCV):* FOCV methods estimate the maximum power point based on the open-circuit voltage of the solar modules, providing an efficient and accurate approach for MPPT.

The incorporation of MPPT technology in PV systems yields several advantages:

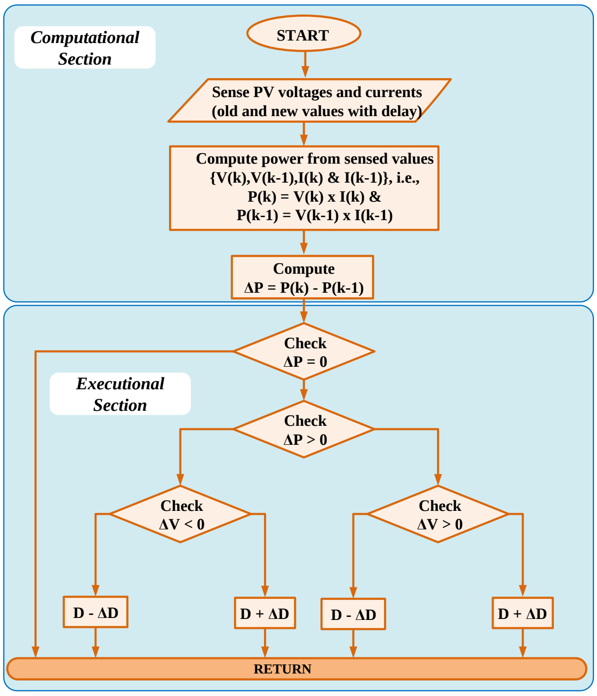

Fig. 2 Perturb and Observe MPPT algorithm

- *Improved Efficiency:* MPPT ensures that the PV system operates at its peak efficiency, minimizing energy losses and maximizing the overall energy output.

- *Adaptability to Changing Conditions:* MPPT algorithms allow PV systems to adapt to variations in sunlight intensity, temperature, and shading, ensuring optimal performance under diverse environmental conditions.
- *Enhanced Return on Investment:* By maximizing energy production, MPPT contributes to a higher return on investment for solar installations, making them more economically viable.

Maximum Power Point Tracking is a crucial technology in the realm of photovoltaics, enabling systems to dynamically optimize their performance and adapt to changing environmental conditions. As solar energy continues to play a key role in the global energy mix, the implementation of efficient MPPT techniques becomes essential for harnessing the full potential of solar power and advancing the sustainability of renewable energy systems.

Power Electronic Interface: HGDC-Boost Converter

The DC-DC boost converter, also known as a step-up converter, plays a crucial role as the power electronic interface in many applications, including photovoltaic systems. Its primary function is to increase the input DC voltage to a higher output DC voltage. This is achieved by utilizing an inductor, a switch (typically a MOSFET), a diode, and a capacitor. The switching action of the MOSFET, controlled by a Pulse Width Modulation signal, stores energy in the inductor during the on-time. When the switch turns off, the stored energy is transferred to the output capacitor through the diode, resulting in a higher output voltage. The voltage gain of the boost converter depends on the duty cycle of the PWM signal [10]. A higher duty cycle leads to a higher output voltage.

The selection of the boost converter components significantly impacts its performance and efficiency. The inductor value influences the current ripple and the converter's transient response. A larger inductor reduces the ripple but increases the size and cost. The switching frequency of the MOSFET affects the converter's efficiency and size. Higher switching frequencies reduce the size of the passive components but can lead to increased switching losses [11]. The diode plays a critical role in preventing reverse current flow and must be selected with appropriate voltage and current ratings. The output capacitor filters the output voltage ripple and determines the converter's output voltage stability.

In photovoltaic systems, the boost converter is often used in conjunction with Maximum Power Point Tracking algorithms to maximize the power extracted from the solar panels. The MPPT algorithm adjusts the duty cycle of the boost converter to match the impedance of the PV array to the load, ensuring that the panels operate at their maximum power point. This is essential for optimizing the overall efficiency of the photovoltaic system. While the high gain DC boost converter offers advantages such as simplicity and low cost, it also faces limitations at high voltage gains due to increased component stress and losses. The schematic diagram of proposed converter and waveform of operation modes is depicted in below figure 3 & 4 respectively.

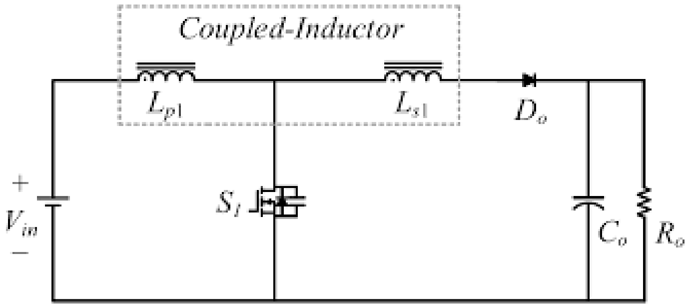

Fig. 3 Schematic diagram of HGDC-Boost Converter Boost Converter

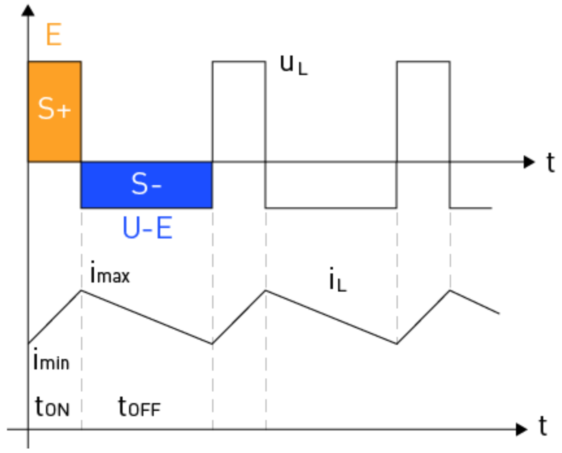

Fig. 4 Operating modes of HGDC-Boost Converter

IV. CONTROL STRATEGY

In this study, the Perturb and Observe (P&O) approach of Maximum Power Point Tracking (MPPT) is utilized. This approach utilizes a DC-DC converter to regulate the photovoltaic (PV) voltage in order to achieve the highest power production. The P&O method, seen in figure 2, is widely favored due to its straightforwardness and execution.

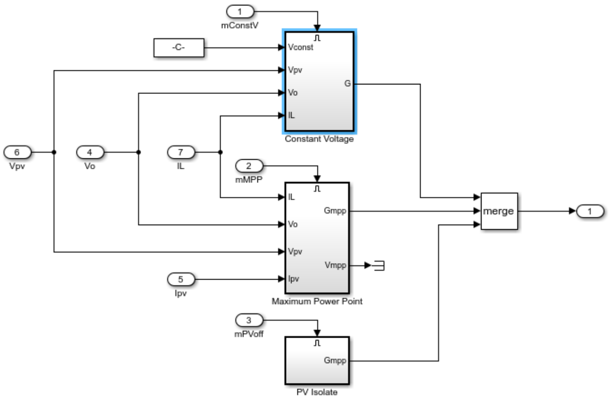

Fig. 5 Simulink Control of DC converter to obtain maximum power from PV system

Essentially, the module's current is disturbed by a little increase, and the subsequent alteration in power is monitored [12]. If there is a positive change in power, the current is modified by the same increment, and the power is once again measured. This continues until the change in power is negative, at which time the direction of the change in current is reversed [13]. The MPPT controller takes V_{pv} and I_{pv} as inputs to detect power slope and generates V_{ref} to track the maximum power point. This V_{ref} is then used to generate firing pulses for the DC-DC converter in closed loop system is shown in Figure 5.

V. SIMULATION RESULT AND DISCUSSIONS

Detailed simulation studies are carried out on 2022a MATLAB/Simulink platform, and the results obtained for standard test conditions are presented in this section. The values of parameters used in the model for simulation are listed in Table I. The steady-state response of the system during the MPPT mode of operation is shown below during slow and drastic changes in input to system. To verify the feasibility of the control strategies, the simulation of 1 kW solar PV system with high gain converter outputs are presented in this section.

Figure 6 shows the simulated waveform of the DC output power from the PV array which demonstrates the effectiveness of the MPPT algorithm in tracking the maximum power point under varying irradiance conditions.

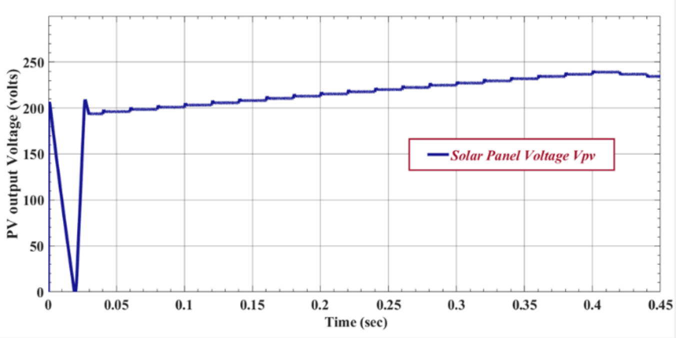

Fig. 6 DC output power from PV array at STC.

The waveform shows how the output power closely follows the available maximum power, even during rapid changes in solar irradiance. Key features to highlight in the waveform and its accompanying description include the settling time of the MPPT algorithm, the magnitude of power oscillations around the MPP, and the overall energy yield.

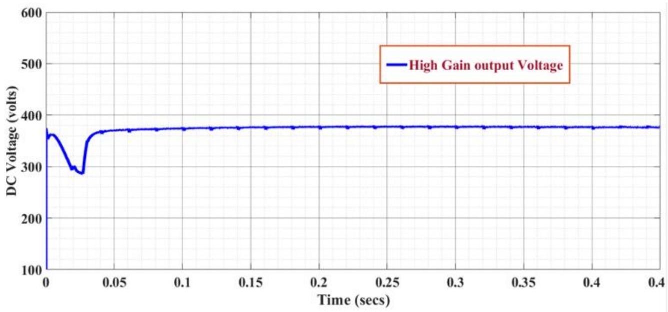

Fig. 7 Output voltage of HGDC Boost converter

Fig. 7 shows the simulated waveform of the DC output power from the high-gain quadratic boost converter which demonstrates its ability to efficiently step up the voltage from the PV array while maintaining stable output power. Key aspects to highlight include the steady-state power level, the ripple magnitude, and the transient response of the converter to changes in input voltage or load conditions. Specifically, the waveform depicts minimal power fluctuations during steady-state operation and a rapid response to changes in irradiance, specific values for output power ripple and transient response time.

In Fig. 8 the simulated waveform of the inductor current in the high-gain quadratic boost converter should exhibit a characteristic sawtooth pattern, reflecting the switching action of the converter. Key features to highlight include the peak-to-peak current ripple, the average inductor current, and the continuous conduction mode of operation for given the high step-up nature of the converter. The inductor current waveform should demonstrate the converter's ability to handle high currents during the charging phase and low currents during the discharging phase.

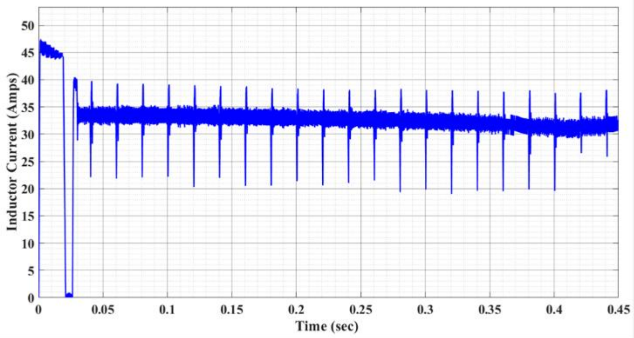

Fig. 8 Inductor current from HGDC Boost converter

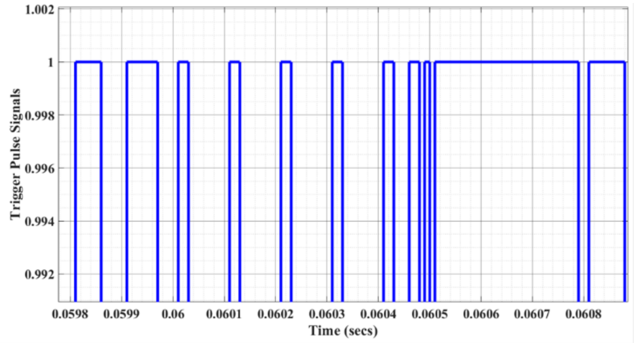

Fig. 9 Gate signals for HGDC Boost converter

From figure 9 the simulated waveforms of the pulsating gate signal for the high-gain quadratic boost converter should clearly illustrate the switching pattern that controls the converter's operation. The signals, typically applied to the MOSFETs switching devices, dictate the timing and duration of the charging and discharging phases of the inductors and capacitors within the QBC. For this high-gain QBC, the gate signals exhibit a specific duty cycle and frequency optimized for achieving the desired voltage boost while minimizing switching losses. The waveforms demonstrate the precise timing relationships between the gate signals for different switches in the converter, highlighting the coordination required for efficient energy transfer. Furthermore, the clarity and sharpness of the rising and falling edges of the gate signals are crucial for minimizing switching losses and ensuring reliable operation. Any deviations from the ideal square wave shape, such as ringing or overshoot, should be minimal.

VI. CONCLUSION

This paper presented the design and implementation of a HGDC boost converter with an improved perturb and observe maximum power point tracking algorithm for photovoltaic applications. The proposed HGDC-Boost Converter successfully achieves a high voltage gain of 10 while maintaining high efficiency and a simplified circuit design. The enhanced MPPT algorithm demonstrated faster dynamic response and reduced power oscillations, ensuring stable operation under fluctuating ambient conditions. Simulation results validated the effectiveness of the proposed approach, highlighting its potential to improve the performance of photovoltaic systems in microgrid applications.

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