An Improved Embedded based PID Controller for Boosting Operation in Solar Energy-Battery Systems

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Abstract

The proposed work introduces an improved PID controller for boosting operation in solar energy-battery systems, leveraging model-based controller (MBC) techniques. In general, boost converters are crucial for managing and optimizing power flow in renewable energy systems. While PID controllers are commonly used in boosting applications due to their simplicity, they often face challenges in adapting to the dynamic and nonlinear characteristics of solar energy systems. This can result in suboptimal performance and efficiency. Hence, a model-based controller with manual tuning is proposed to improve the stability and efficiency by systematically tuning controller gain parameters based on its system model. Extensive simulation studies conducted using MATLAB/Simulink shows that the proposed controller outperforms the conventional PID controller under various operating conditions, such as fluctuations in solar irradiance and changes in battery state of charge. Further, the experimental tests conducted on a prototype setup validates the feasibility and ability of the model-based controller to accurately regulate the solar panel output and efficiently charge the battery, which leads to enhanced performance. This work offers a promising solution for enhancing energy conversion efficiency and facilitates the effective integration of renewable energy sources into the power grid.

Keywords: PID Controller, Boost Converter, Solar Energy, Battery Management, Model-Based DC-DC Controller, Embedded Controller

1. Introduction

The sun, a celestial powerhouse, provides a plentiful and clean source of renewable energy. However, effective harnessing solar energy presents a distinct challenge. One way to overcome this challenge and to unlock the sun's full potential for reliable power supply is through an effective integration between the panel and the battery, which also demands a careful management. Under such circumstances, maintaining a delicate balance between efficiency and stability becomes crucial [1].

Generally, solar radiation is intermittent in nature, causing the output generated by solar panels to fluctuate with solar irradiation and ambient temperature. From the literature, it is evident that the state of charge of battery also significantly affects the battery voltage [2], [3]. To feed a constant voltage to battery, a boost converter is generally preferred between the solar panel and the load. The key challenge in a boost converter is to maintain a stable and regulated output voltage despite variations in input voltage and load conditions. In boost converters, PID controllers are normally preferred to control the output voltage by adjusting the duty cycle of the switch in the converter using PWM techniques to ensure stability and efficiency. High-quality output voltage can be obtained by adopting advanced tuning algorithms in the PID for specific operating ranges and loading conditions [4]. Though PID controllers provides reliable control and primarily used for voltage regulation, their performance can sometimes be suboptimal due to its limited integration and flexibility issues [5],[6]. They also require frequent tuning to handle varying environmental conditions effectively. To overcome these challenges, many researchers recommend a model-based approach for tuning PID controllers in solar energy-battery systems [7],[8].

In the model-based approach, developing a comprehensive mathematical model allows for efficient capturing of the system's dynamic behavior, including the battery and boost converter, leading to enhanced battery charging/discharging efficiency, reduced energy losses, and prolonged battery lifespan [9], [10]. The model serves as a virtual representation, enabling detailed analysis of system response to varying operating conditions. By analyzing the model's responses in various scenarios such as fluctuating solar irradiation and varying battery loads, it seeks to fine-tune the gains for enhanced voltage regulation and efficiency. The model based

optimized controller is anticipated to deliver a more stable and predictable power output from panels to the battery while compared to conventionally tuned controllers [11], [12]. Better control over voltage ensures a more dependable system, lowering the chances of harm to connected devices. Moreover, enhanced efficiency allows for the maximization of harvested solar energy, thereby reducing energy wastage.

Hence, in the recommended method, an embedded-based PID (Proportional-Integral-Derivative) controller is used, where a PID control algorithm resides in embedded systems and utilizes the mathematical model of the system to improve the tuning and performance. When the solar irradiance, ambient temperature, and load profiles vary throughout the day or across seasons, the model-based controller allows the PID controller to adapt dynamically. The controller can adjust its response based on real-time data and predict the system behavior, ensuring optimal performance under diverse operating scenarios without manual intervention. This model-based controller empowers the solar battery systems with intelligent, data-driven control strategies that optimize energy utilization, improve system reliability, and prolong the lifespan of batteries, making it a valuable approach for maximizing the performance and efficiency of solar energy storage systems.

In a nutshell, the proposed idea aims to take a significant step forward in transforming solar energy into a highly optimized, efficient, and reliable source of power.

2. Related Work

In the existing solar energy-battery systems, for generating a regulated output from the panel mostly PID based DC-DC controllers are preferred and its performance heavily depends on the proper tuning of the proportional, integral, and derivative gains to achieve desired system performance. Generally, these controllers are tuned on traditional methods, such as trial-and-error process, Ziegler-Nichols method, Cohen-Coon method to find the optimal parameters for specific applications [13], 14] and [18]. The PID based DC-DC boost converter shown in the Figure.1 comprises of controllable switch (S), inductor (L), Capacitor(C), Diode (D) with sensor circuit for voltage and current measurement and PID controller. The output voltage of the converter is regulated by controlling the firing pulses to the switch by employing PID based PWM generation with PID controllers tuned on traditional methods. Though the

above methods depend on operators' expertise to achieve desired performance, due to their simplicity and cost-effective nature, they are widely preferred for control applications. However, during some unavoidable situations, this may also lead to sub-optimal performance.

Due to advancements in software-based optimization tools in recent days, various soft computing techniques are widely employed for PID tuning. Among these techniques, fuzzy-based PID tuning not only improves transient response but also ensures satisfactory steady-state responses. [6]. This software-based optimization tool for PID tuning is complex and requires significant computational power and expertise to use effectively. Additionally, they can be costlier, with potential ongoing expenses for licensing, updates, and support.
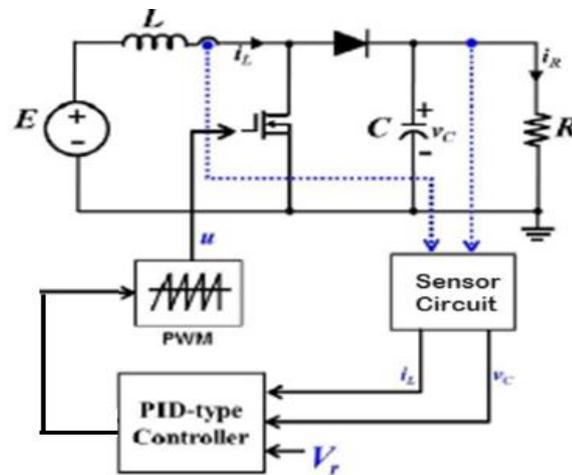

Figure 1. PID based DC-DC Boost Converter

In addition, during the fluctuations in the output due to ever changing nature of solar radiation and battery charge levels, the system encounters several challenges in achieving optimal controller settings. This can lead to suboptimal performance and reduced efficiency of the DC-DC converter system [15]. Furthermore, conventional PID controllers may face difficulties in maintaining stability in systems with high levels of noise or disturbances. Solar energy systems are often subject to fluctuations in sunlight intensity and other external factors, which can introduce noise into the system. Conventional PID controllers may struggle to filter out this noise and maintain stable operation, leading to performance issues and potential damage to the system components. This situation leads to several stability issues. [16], [17]. Though conventional PID controllers are widely used in a variety of control applications, they may not be ideally suited for the unique challenges posed by solar-powered DC-DC converters.

Hence, there exists a need to provide an alternative solution for improving controller performance under all environmental conditions.

Alternative control strategies, such as model-based tuning or advanced control algorithms may offer better performance and efficiency in these applications. Hence, it is suggested here to use embedded model-based controller tuning approach to systematically adjust the PID controller parameters based on the system's dynamic model. It also improves its ability to adapt to changing conditions and nonlinearities with a minimum cost and complexity.

Section 3 and 4 clearly explains the methodology and results obtained for the suggested embedded model-based PID for Solar-battery systems.

3. Proposed Work

The key innovation in the proposed system lies in the implementation of PID algorithm on a PIC microcontroller, leveraging a technique called Embedded Model-Based Controller. The block diagram of the proposed work is shown in the Figure 2. In this work, Maximum Power Point Tracking (MPPT) algorithm is used to find the true maximum power operating point of the solar panel. Initially, the mathematical model of the PID controller is obtained in which the controller parameters are identified by trial-and-error approach by iterative adjustments of the proportional (K_p), integral (K_i), and derivative (K_d) gains to achieve the desired system performance. A general thumb rule is used in identifying and fine tuning the controller parameters. A voltage and current sensors are used to measure the voltage and current output of boost converter. A PIC microcontroller is used here with sufficient processing power, analog-to-digital converters (ADCs) and inbuilt PID algorithm to read the output from sensors and to generate the control signals. Hence, the control signal from PID controller adjusts the duty cycle of the boost converter to regulate the output voltage and MOSFET is used as actuator for switching the boost converter.
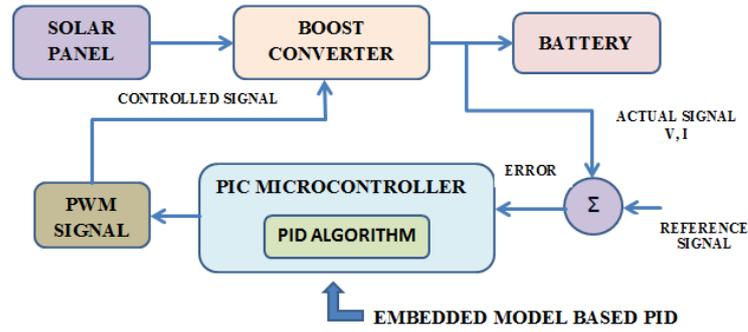
Figure 2. Block Diagram of Embedded Model based PID Controller

The proposed controllers offer a real-time adjustment which is crucial for dynamic systems ensuring stability and adaptability under fluctuating environment conditions. This method continuously optimizes the PID gains to achieve superior voltage regulation, efficiency, making them ideal for providing optimum performance in Solar PVs system and optimal energy management.

The proposed embedded model-based PID controller is shown in Figure.2. It consists of various components as given in the Table.1. The detailed description of components is given below:

- **Solar Panel**

The solar panel works under the principle of photovoltaic effect. Through this process, PV cells convert sunlight into electricity. It produces a variable voltage output depending on sunlight intensity, which is then fed to the converter in the next stage.

Table 1. Components used in Proposed System

Components	Description
Solar Panel	Converts sun radiation to electricity. (25W,12V)
MOSFET(P55)	Switches the current in boost converter
Capacitor	For filtering purpose
Battery	Energy storage for the system

Inductor	Stores and releases energy in a magnetic field
Ultrafast Diode	For a high frequency operation
PIC Microcontroller	Implements PID controller algorithms
Load	Utilizes the converter output voltage

- **DC-DC Boost Converter**

The converter takes the variable output voltage from the panel and boosts it to a stable output voltage suitable for charging the battery. It uses MOSFETs for switching and an inductor for energy storage and regulation. Its output is then controlled by the PIC microcontroller using a PID algorithm.

- **Battery**

The battery stores the energy generated by the panel for later use. It is charged by the DC-DC converter and provides power when there is no sunlight. The ultrafast diode restricts the flow of reverse current to the battery from the converter [21].

- **PIC Microcontroller with PID Algorithm**

The PIC microcontroller controls the function of the converter. It implements a PID algorithm for optimal voltage regulation. The microcontroller also monitors system parameters and adjusts the converter's settings accordingly.

- **Electrical Load**

The electrical load consumes the energy produced by the system. Here the load resistor simulates a real-world load that the DC-DC converter would typically power. The output voltage is measured using a multimeter connected across the load resistor.

- **Ultrafast Diode**

The ultrafast diode rectifies the voltage output from the DC-DC converter and prevents reverse current flow. It ensures that energy flows only in the desired direction, maintaining the stability of the system.

The proposed embedded model-based controller is implemented in software and allowed to run on PIC microcontroller unit. The implementation involves writing code that continuously reads sensor data (panel voltage and current), calculates the error, and adjusts the control outputs to drive actuators or other control elements to achieve the desired set point.

a. Working

The solar panel generates a voltage around 12V, depending on sunlight intensity. The DC-DC (Boost) converter increases the voltage from 12V to a higher level suitable for battery charging. The specific boost ratio depends on the converter design. In this case, the boost ratio of will be approximately 4.2-4.4 to achieve an output voltage in the 50-53V from a 12V input. The PIC microcontroller continuously monitors the actual voltage and current at the battery terminals using an analog-to-digital converter (ADC). It calculates the difference between the actual battery voltage and the desired reference voltage (set to 51.5V).The PID algorithm in the PIC microcontroller utilizes the chosen K_p, K_i, and K_d values (0.5, 0.2, and 0.1) to adjust the PWM control signal for triggering the MOSFET based on the calculated error. These gains were optimized using simulation tools to achieve the desired performance metrics, such as fast response time, minimal overshoot, and stable operation under varying conditions.

By continuously monitoring the error and adjusting the MOSFET switching pattern through the PWM signal, the PID algorithm strives to maintain the battery voltage within the target range (50-53V) despite fluctuations in solar panel output or changes in load conditions. Hence, the proposed model pretends to be working in adaptive control mode. Unlike the pure manual method of tuning, this technique reduces the time in obtaining the optimal PID gains, ensuring peak performance.

4. Results and Discussion

The implementation of the embedded based PID controller for the solar energy-battery system yielded significant improvements in performance and efficiency.

The Simulink model and its output of the proposed method is shown in the Figure 3 and 4 respectively. The optimal tuning values for Kp, Ki, and Kd depend on specific system components and desired performance characteristics. Through the iterative tuning process, the final set of values is obtained that effectively regulate the battery voltage. This final set might be close to the initial values say Kp = 0.5, Ki = 0.2, and Kd = 0.1. These gains were optimized using simulation tools for desired performance metrics, such as fast response time, minimal overshoot, and stable operation under varying conditions.

With those controller gain, the PID controller effectively regulates the output voltage to maintain it within the desired range of 50-53V, even under varying load conditions. This regulation ensures stable and reliable power delivery to the load, enhancing the overall efficiency of the system.
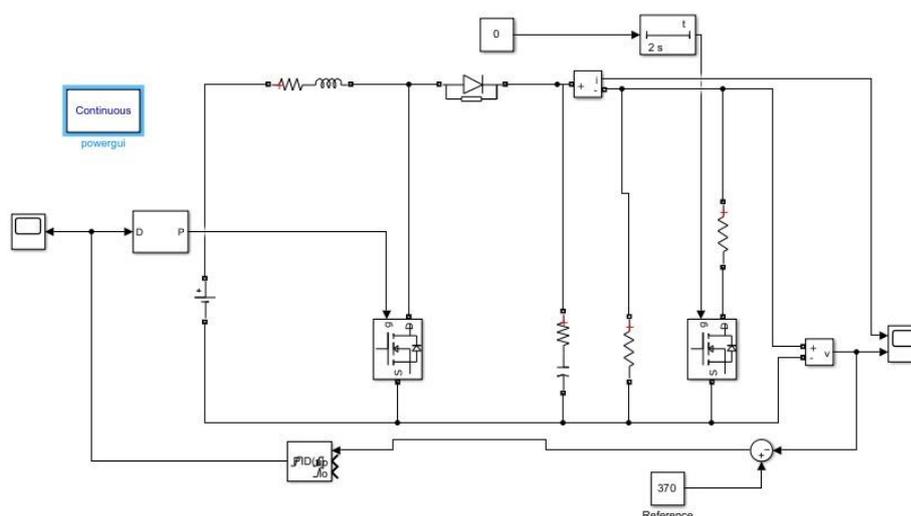

Figure 3. Simulink Model for Model-based DC-DC Boost Converter

The specific PID algorithm within the PIC microcontroller is implemented. It calculates a control output based on the following equation:

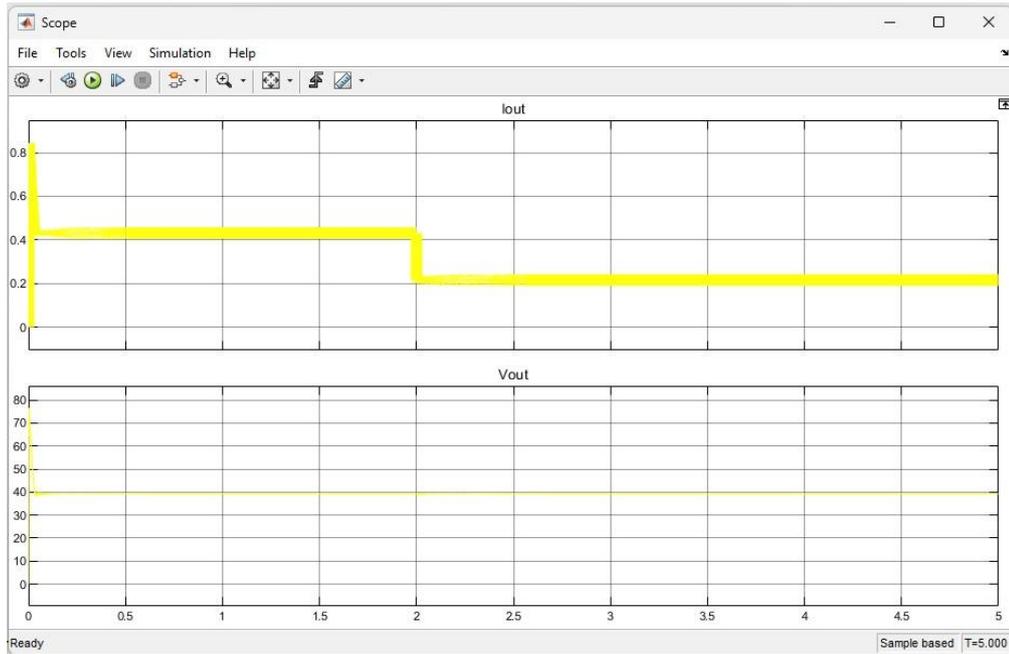$$Control\ output = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

(1)

Figure 4. Simulink Output for Model-based DC-DC Boost Converter

Compensator formula used:

$$P + \frac{I}{s} + D\left[\frac{N}{1+N^{1/s}}\right]$$

(2)

PWM Duty Cycle:

$$D = \frac{\left(\dfrac{V_{out}}{V_{in}}\right)}{\left(1+\dfrac{V_{out}}{V_{in}}\right)}$$

(3)

The prototype model of the proposed system is shown in Figure 5.

(i) Model-Based PID Controller Design

A mathematical model of the converter system is developed and is used to determine the PID controller gains (K_p, K_i, and K_d) for optimal power utilization. The model-based approach ensured that the controller parameters were tuned to the specific characteristics of the system, leading to improved performance and efficiency.

(ii) PID Controller Gains Determination

Through the model-based approach, the PID controller gains were determined to be K_p = 0.5, K_i = 0.2, and K_d = 0.1. These gains were optimized using simulation tools to achieve the desired performance metrics, such as fast response time, minimal overshoot, and stable operation under varying conditions.

(iii) Implementation on PIC Microcontroller

The control system, including the PID controller was implemented on a PIC microcontroller for real-time operation. The use of ladder logic programming in the microcontroller ensured minimal hardware complexity and efficient execution of the control algorithm.

(iv) Performance Evaluation

The implemented PID controller was evaluated in real-time operation with a dedicated solar PV system under varying test conditions (i) Varying illumination (ii) Varying temperature (iii) Varying load. Under all the test conditions the controller demonstrated improved performance compared to a conventional PID controller, with faster response time and better stability.

The performance of embedded model-based PID controller is given in Table.2. It shows that the proposed controller offers better efficiency and it was also observed that the system responds quickly and accurately to changing load and input conditions when compared to conventional PID controller.

Further the proposed controllers ensure the following benefits:

- It optimizes the boost converter operation effectively hence, the system can maintain the solar panel at their Maximum Power Point (MPP), thereby ensuring maximum energy conversion efficiency.

- The adaptability nature to varying environmental conditions helps in maintaining optimal performance despite the dynamic nature of solar energy, which directly translates to higher energy conversion efficiency.

- It ensures stable and dependable power supply from solar panels to the battery system and ultimately to the power grid. This stability is essential for grid integration, as it reduces fluctuations and harmonics that could otherwise disrupt grid operations.

- It optimizes charging and discharging cycles of battery effectively, which not only extends battery life but also enhances energy utilization during times of reduced solar output. This efficient battery operation is vital for maintaining a steady energy supply to the grid, particularly during periods of minimal solar activity.
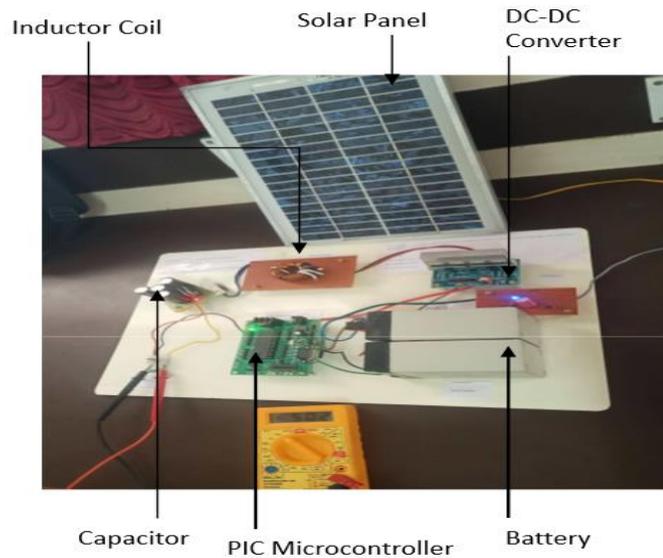

Figure 5. Prototype Model of the Proposed System

Table 2. Comparison between Existing Method and Proposed Method

Controllers	Panel Output	Boost Converter Output	Efficiency
Under Constant Illumination, Temperature and Load			
Conventional PID	12V	30	88%
Embedded Model-based PID	12V	50	96%
Under Varying Illumination, Temperature and Load			
Conventional PID	12V	30	86%
Embedded Model-based PID	12V	50	94%

Hence, the proposed work provides a more comprehensive solution by enhancing energy conversion efficiency, ensuring stable and reliable power supply, and making solar energy systems more grid-compatible. The encoded data and their interpreted outputs are tabulated in Table 2.

5. Conclusion

The proposed method focuses on the implementing an improved embedded model-based PID controller in Boost Converter to regulate the electrical output of a solar energy-battery system. Implementing a model-based PID controller in solar energy-battery systems shows significant improvements in stability and efficiency compared to traditional PID controller tuning methods. Tuning parameters based on the system model enhances the controller's ability to adapt to dynamic and nonlinear conditions leading to increased power flow and improved overall system performance. The idea successfully addressed voltage regulation challenges in a solar-battery system. By implementing the model-based PID controller for the boosting applications, the system is expected to achieve significant improvements compared to the existing control strategy.

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