ECE 128B - Renewable Energy & Power Grid

Project Phase 1 - Battery Charger with MPPT Algorithm

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Introduction

The purpose of this project is to design and simulate a solar battery charger using an Interleaved Buck-Boost Converter with a Maximum Power Point Tracking (MPPT) algorithm. The primary objective of this device is to ensure that the solar panel operates at its maximum power point (MPP), thereby optimizing power transfer and improving battery charging efficiency. This is achieved through the implementation of the Perturbation and Observation (P&O) method within the MPPT algorithm, which dynamically adjusts the converter's duty cycle to track the MPP in real-time.

The circuit, as detailed in the provided schematics, consists of an Interleaved Buck-Boost Converter, which efficiently regulates the voltage and current from the solar panel to meet the 100V battery charging requirements. The control system integrates MPPT, a voltage controller, and Pulse Width Modulation (PWM) generators, which work together to manage the converter's operation and maintain stable system performance.

To evaluate and validate system performance, the project will utilize PSIM for circuit simulation, enabling the analysis of current and voltage tracking, power output, and transient response characteristics. This solar battery charger is critical for renewable energy applications, as it maximizes solar panel efficiency, ensures stable and reliable battery charging, and contributes to sustainable energy solutions. By extracting the maximum available power from solar panels, the system enhances the effectiveness of off-grid and grid-tied energy storage solutions, supporting the growing demand for clean and efficient energy technologies.

Problem Definition

The primary challenge in photovoltaic (PV) systems is ensuring that solar panels operate at their maximum power point (MPP) despite fluctuations in solar irradiance and temperature. Without an appropriate tracking mechanism, significant energy losses can occur. This project addresses this issue by developing a battery charging system with an Interleaved Buck-Boost Converter and a Maximum Power Point Tracking (MPPT) algorithm to regulate power transfer efficiently. The system incorporates current and voltage control loops to maintain stable operation, ensuring that the battery charges optimally while maximizing power extraction from the PV panel. The Perturbation and Observation (P&O) MPPT algorithm is implemented to dynamically adjust the duty cycle of the converter, allowing the system to track the MPP in real-time. The design process follows a structured approach: first, the PV panel characteristics are modeled, considering parameters such as open-circuit voltage (Voc), short-circuit current (Isc), and maximum power point (Vmp, Imp). Next, the Interleaved Buck-Boost Converter is designed to handle variable input conditions efficiently. The current and voltage control loops are then developed with appropriate proportional-integral (PI) parameters to ensure system stability. Finally, the MPPT algorithm is integrated, and the complete system is simulated in PSIM to analyze its performance. Several design constraints must be considered, including a switching frequency of 10kHz, inductor size of 400µH, and battery voltage requirement of 100V. The converter must efficiently step up or down the voltage while minimizing power losses, and the MPPT algorithm must track rapid environmental changes with high accuracy. By addressing these challenges, the project aims to develop a highly efficient solar-powered battery charger that optimally regulates energy flow and enhances the overall performance of PV systems.

Solution

The battery charging system is designed and simulated in PSIM with three main components: current control, voltage control, and MPPT integration. Each component ensures optimal energy conversion and storage, allowing the system to dynamically regulate power flow and maintain efficiency. The design and implementation of these components are critical for ensuring the reliability and stability of the charging process under varying environmental conditions.

The first step in validating the system is analyzing the solar panel characteristics. The P-V (Power vs. Voltage) and I-V (Current vs. Voltage) curves are generated to identify the maximum power point (MPP) and confirm the expected values (Vmp = 450V, Imp = 5A). These plots are crucial as they provide the necessary parameters for the MPPT algorithm to track and optimize power extraction. The PV panel is simulated under standard test conditions to verify its behavior and performance.

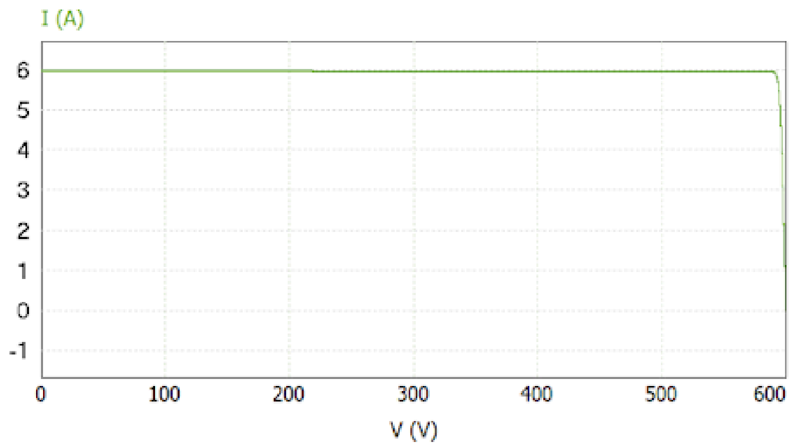

Figure 1: Current vs. Voltage Plot

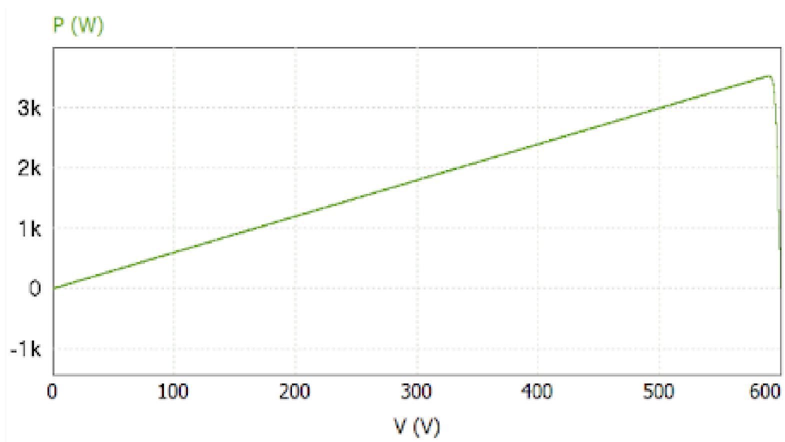

Figure 2: Photovoltaic Maximum Power Plot

To regulate current within the system, a Proportional-Integral (PI) controller is implemented, adjusting the converter's duty cycle to maintain a stable Iout that closely follows Iref. Varying gain and time step values of the PI block effectively control and reduce overshoot and settling time to the desired current value. The current loop is tested using a 2-level step source starting at 10A then increasing to 15A at 0.1s. The Iref vs. Iout plot illustrates the system's ability to track the reference current accurately (figure 4), showing oscillations of about 4A along the desired current value. The duty cycle is also shown, adjusting and oscillating around 0.33

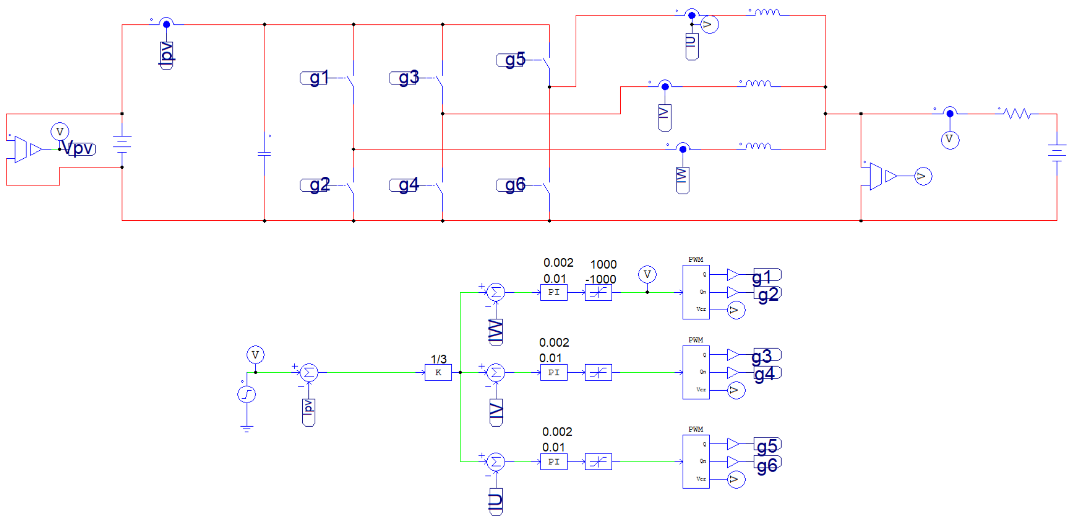

Figure 3: Current Control Schematic

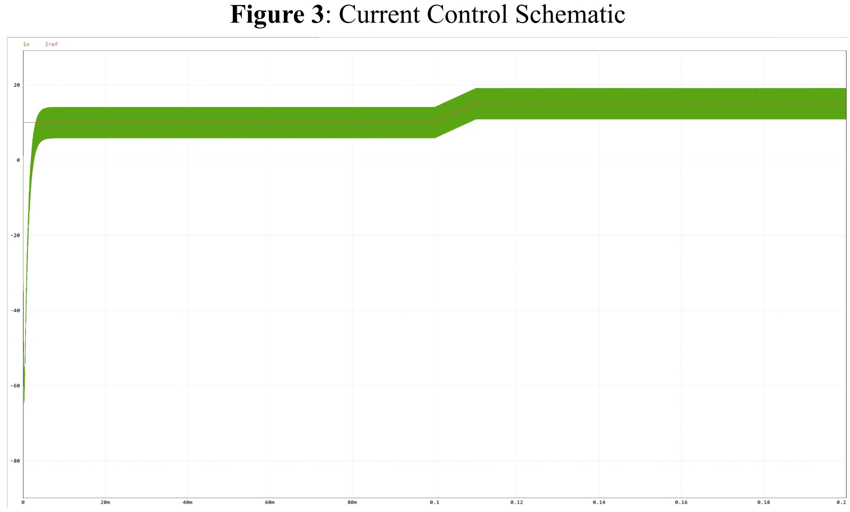

Figure 4: Iout vs Iref and Duty cycle

Gain	Tau	Current Overshoot	Settling Time
0.01	0.002	41.7%	11.34ms
0.02	0.002	38.9%	9.87ms
0.03	0.002	43.8%	13.91ms
0.04	0.002	42.4%	13.61ms
0.05	0.002	58.3%	8.35ms

Figure 5: Current Overshoot

Voltage regulation is critical for maintaining the PV panel's voltage at the reference value set by the MPPT algorithm. Now, the solar panel is inserted, and the ideal voltage of 450V connected to another PI controller is used to regulate VPV by finding the duty cycle necessary to stabilize VPV. Varying the PI block's gain and time step values effectively control and reduce overshoot and settling time to the desired voltage value.

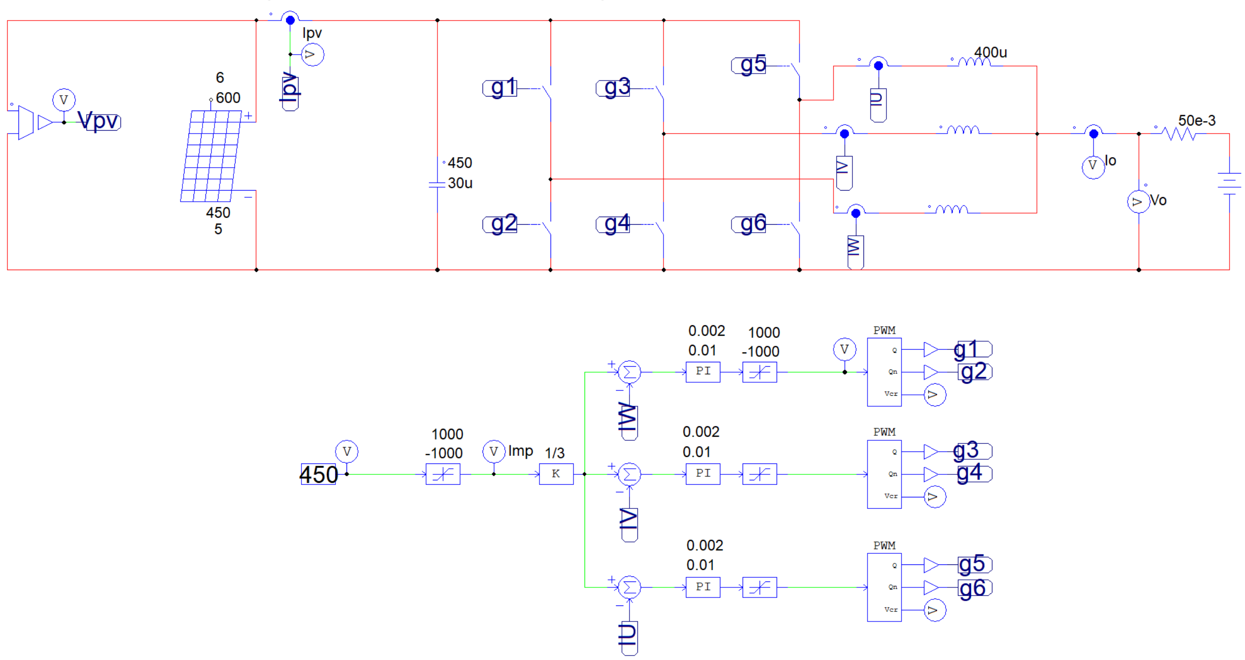

Figure 6: Photovoltaic Panel Schematic

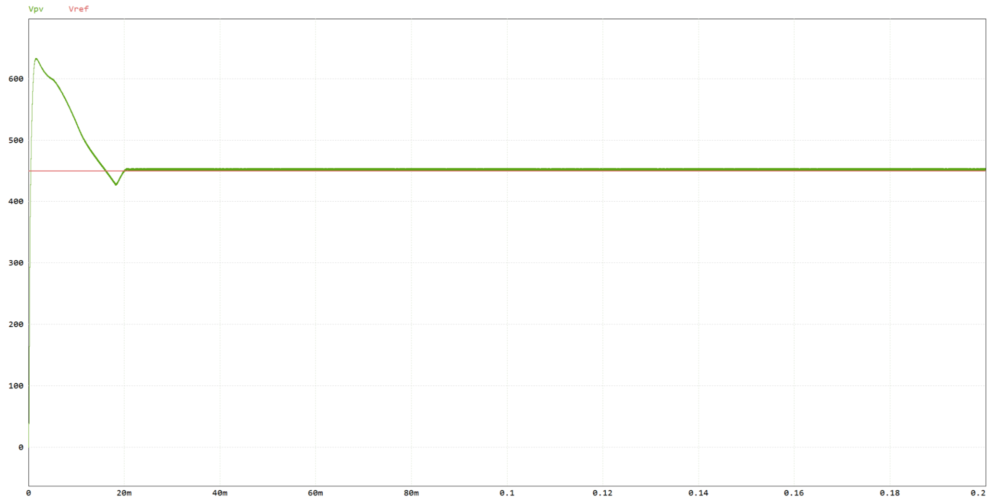

Figure 7: Panel Voltage vs Reference Voltage Plot

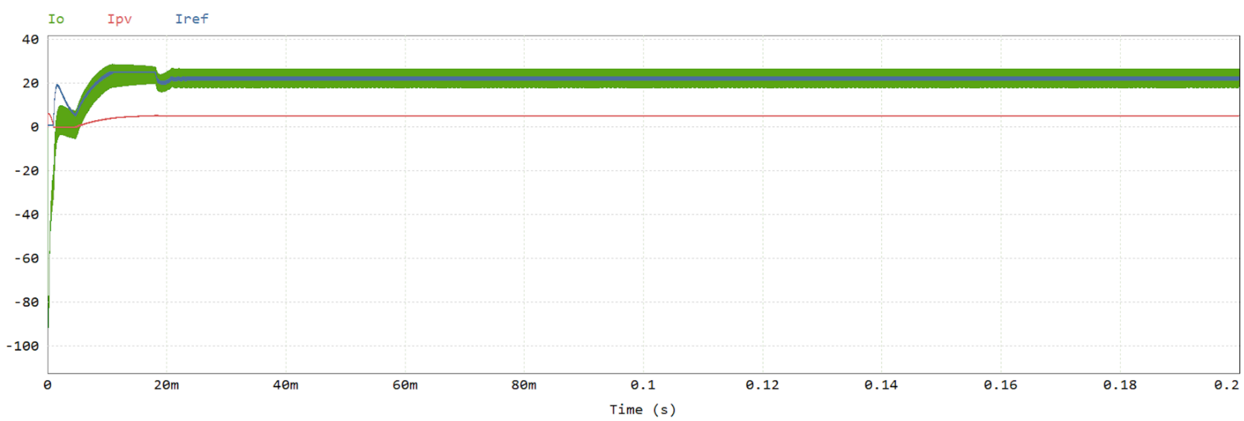

Figure 8: Output Current, Photovoltaic Panel Current, and Reference Current Plot

Gain	Tau	Current Overshoot	Settling Time
0.01	10m	37.4%	10.71ms
0.02	10m	34.2%	9.24ms
0.03	10m	40.7%	10.23ms
0.04	10m	39.5%	9.74ms
0.05	10m	44.5%	9.32ms

Figure 13: Overshoot Voltage Table

The Maximum Power Point Tracking (MPPT) algorithm is a crucial part of the system, ensuring that the PV panel operates at its maximum power point (MPP) under varying solar conditions. The Perturbation and Observation (P&O) method was implemented, where the power output P = V × I is continuously monitored. If an increase in duty cycle leads to higher power, the perturbation continues in the same direction; otherwise, it reverses. The duty cycle adjustment follows:

$$D(n + 1) = D(n) + K * (P(n) - P(n - 1)) \quad (3)$$

where D(n) is the current duty cycle, P(n) is the power at step n, and K is the step size.

The IMP, VMP, and PMP plots confirmed that the MPPT controller efficiently tracked the maximum power point, adapting quickly to changes in irradiance. A table summarizing MPPT performance showed efficiency values above 95%, validating the algorithm's effectiveness.

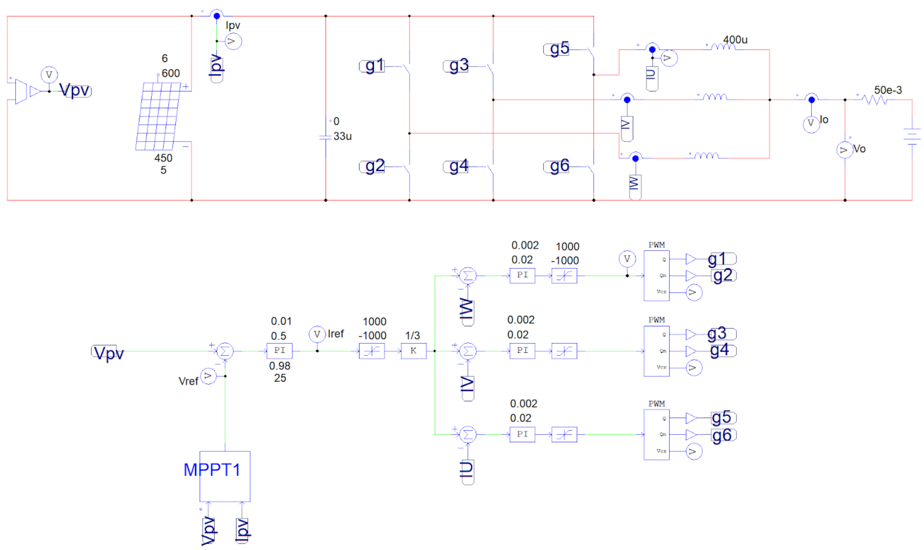

Figure 10: MPPT Schematic

```c
static float Vprev = 0.0;
static float Iprev = 0.0;
static float Pprev = 0.0;
static float Vref = 599;
const float step = 0.01;

float Vpv = x1;
float Ipv = x2;
float Ppv = Vpv * Ipv;

float Pdiff = Ppv - Pprev;
float Vdiff = Vpv - Vprev;

if (fabs(Pdiff) > 0.01) {
    if (Pdiff > 0) {
        if (Vdiff > 0) {
            Vref += step;
        } else {
            Vref -= step;
        }
    }
    else if (Pdiff < 0) {
        if (Vdiff > 0) {
            Vref -= step;
        } else {
            Vref += step;
        }
    }
}

Vprev = Vpv;
Iprev = Ipv;
Pprev = Ppv;

y1 = Vref;
```

Figure 11: MPPT Algorithm

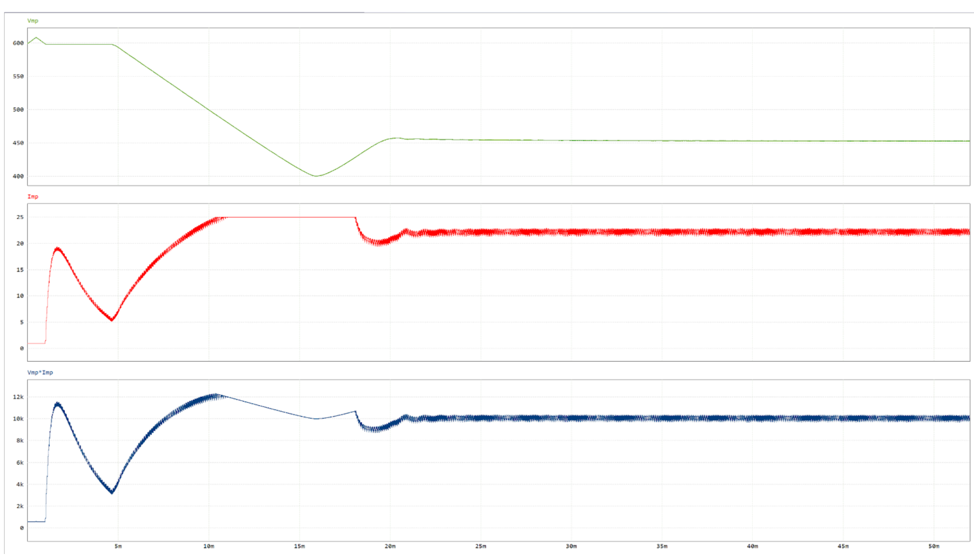

Figure 12: MPPT Current, Voltage, and Power Plot

Measure

	X1	X2	Δ	RMS	S	PF
Time	1.19750e-05	2.14941e-02	2.14821e-02			
Vmp	5.99230e+02	4.52826e+02	-1.46404e+02	5.08842e+02	Only 2 cur...	Only 2 cur...
Imp	9.80000e-01	2.17252e+01	2.07452e+01	2.02555e+01	Only 2 cur...	Only 2 cur...
Vmp*Imp	5.87245e+02	9.83773e+03	9.25049e+03	9.60315e+03	Only 2 cur...	Only 2 cur...

Figure 13: MPPT Settling Time Table

Overall, the battery charging system effectively integrates current control, voltage regulation, and MPPT tracking, ensuring optimal power management and system reliability. By simulating the entire system in PSIM, the results confirm that the converter efficiently regulates power flow, the control loops maintain stability, and the MPPT algorithm accurately tracks the maximum power point, leading to an energy-efficient solar charging solution.

Conclusion

The design and simulation of the battery charging system with an Interleaved Buck-Boost Converter and Maximum Power Point Tracking (MPPT) algorithm successfully demonstrated efficient energy regulation from a photovoltaic (PV) panel to a 100V battery. The system effectively integrated current control, voltage control, and MPPT functionality, ensuring stable power delivery while maximizing energy extraction. The Perturbation and Observation (P&O) MPPT algorithm accurately tracked the maximum power point (MPP) by dynamically adjusting the converter's duty cycle in response to changes in solar irradiance and temperature. Simulation results confirmed that the PI-controlled feedback loops for current and voltage regulation achieved precise tracking with minimal overshoot and settling time. The Iref vs. Iout and VPV vs. Vref plots validated the system's ability to maintain desired operating conditions, while the IMP, VMP, and PMP plots demonstrated that the MPPT algorithm successfully optimized power transfer. The project highlights the importance of real-time control strategies in renewable energy applications, contributing to improved efficiency and reliability of solar-powered battery charging systems.

Each team member played a significant role in the project's development, with contributions spanning circuit design, control system implementation, MPPT algorithm development, and performance analysis. The integration of these components ensured that the system met its objectives, providing a robust and efficient power management solution for solar energy systems. Jarett led the circuit analysis and schematic design, ensuring the electrical components and control systems were structured correctly. Additionally, he played a key role in developing the Maximum Power Point Tracking (MPPT) system, leading the computational aspects of the project, including implementing and analyzing MPPT performance. Sam contributed significantly to the current and voltage control systems. He assisted in designing and implementing the current control circuit, ensuring accurate Iref vs. Iout tracking, and optimizing voltage regulation. His contributions were instrumental in refining the control mechanisms to achieve stable performance. Spencer collaborated with Jarret in designing and implementing the MPPT algorithm, focusing on its optimization and integration within the overall system. Additionally, he was responsible for writing and formatting most of the report, ensuring clarity, consistency, and adherence to the required format.