Topology of a Three-Port Converter for High-Altitude Platforms

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This work was supported by the Strategic Priority Research Program of China Academy of Sciences under Grant XDA17020304.

ABSTRACT
Three-port converter (TPC) with non-regulated bus cannot meet the voltage stability demands of high-altitude platforms (HAPs) during daytime operations. In contrast, full-regulated bus TPC is complex in topology and inferior in power density, although it can maintain voltage stability across whole day operations. Therefore, semi-regulated bus TPCs are more suitable for this scenario, which can not only maintain voltage stability during daytime operations, but also have simple topology. However, conventional semi-regulated bus structure converts the power twice, leading to lower efficiency and power density. In order to overcome this problem, the paper proposes a novel semi-regulated bus TPC that can be used on high-altitude platforms. The topology only has one conversion between the ports. It regulates the bus voltage during the day and prevents the loss of diode during the night by directly discharging through the MOSFET and achieving high efficiency. The paper adopts GaN devices to elevate the working frequency to further improve the power density, and conduct a theoretical analysis for all working modes and provide key equations. The closed-loop transfer function of the system is deduced for stability analysis. The results show that the proposed topology has high efficiency and power density.

INDEX TERMS
Aerospace vehicles, boost, high efficiency, semi-regulated bus, three-port converter.

I. INTRODUCTION
Near space is defined as an altitude of 20 to 100 km. Due to its unique environmental conditions, near space has become a focus for global research and development [1], [2]. Common high-altitude platforms include, but are not limited to, high altitude balloons, stratospheric airships, near-space solar Unmanned Aerial Vehicles (UAVs) and so on [3]. Their energy systems usually adopt a photovoltaic-energy storage topology, in which the energy management unit feeds the power from solar panels to the loads and stores the surplus in batteries during the day and powers the loads from batteries during the night. Through the balancing of energy during the day and night, long-endurance missions can be achieved [4], [5]. Figure 1 shows the HAPs we have developed.

The energy management unit usually consists of multiple DC/DC converters. To control the circuit parameters and energy flows, each DC/DC circuit should have respective control functionalities, including constant voltage output control, constant current output control and max power point tracing (MPPT) control. The photovoltaic-energy storage topology usually has a photovoltaic input port, a bidirectional battery port and a load output port. Therefore, such an energy conversion circuit is also known as a three-port converter [6].

FIGURE 1. Self-developed HAPs using three-port converters.
For usage on HAPs, the topology of the TPC should have high conversion efficiency, power density and reliability. The TPC used on HAPs have common framework which is showed in Figure 2.

According to whether there is direct electrical connection, the circuit is divided into isolated and non-isolated types [7]. Isolated converters use a high-frequency transformer to avoid shock hazard and extend the voltage conversion ratio. But the high-frequency transformer will make it hard to increase power density and efficiency of the converter [8]. Both the power density and efficiency are the most critical factors in the power system design process for HAPs. Therefore, non-isolated TPC is more suitable for this environment [9].

In [10], a soft switching interleaved boost converter is proposed where efficiency was 98.78% at power of 798W. But the converter is working at 25 kHz without using GaN HEMT which leads to low power density. A high power conversion capability with limited weight is a key index of the energy system. As a third-generation semiconductor, GaN-based wide bandgap power devices can greatly increase the working frequency of the circuit [11].

Since the number of inductors and capacitors in a switching circuit decrease with the switching frequency, the weight of the circuit is reduced. Using enhancement-mode gallium nitride field effect transistors (eGan FETs), Xue et al. proposed a non-isolated boost circuit with a frequency of 1 MHz and a power of 130 W was implemented [12]. Through a soft switching technique, the efficiency reached 96%. However, the topology is a dual-port DC/DC circuit with two switches and two inductors. Therefore, this low integration is not suitable for the three-port requirements of HAPs.

As a DC converter consisting of multiple DC/DC modules in series and parallel, the TPC is capable of improving the power density through multiplexing sub-circuits that are of identical structure or the same functionality [13]. A non-isolated TPC powered by a fuel cell and Li-ion battery featuring power backup and a high step-up has been proposed [14]. The system requires two inductors and an additional switching capacitor circuit to achieve high step-up. Otherwise, the backup function of unidirectional output power cannot be used on HAPs without photovoltaic input. Tomasz-Manez et al. [15] proposed a TPC consisting of PV and energy storage parts. In their topology, energy can flow bidirectionally between any two ports, thereby greatly improving the efficiency. Although their 4 kW prototype has an efficiency of 97%, it requires more switches, which is disadvantageous for control strategy and system stability.

However, the more porters in a circuit the more focus should be given on reliability. A renewable energy multi-port network consisting of five ports was proposed [16]. The unified converter topology and the high integration of the digital control system improves reliability. The conversion from multiple input sources and the AC loads introduce inconsistency, rendering it unsuitable for HAP working scenarios.

We propose a semi-regulated bus TPC topology with integrated inductor multiplexing. In our design, the two boost circuits share one inductor, thereby reducing the number of magnetic components. In addition, the working frequency is elevated to 200 kHz, thereby greatly reducing the weight from inductors and capacitors. Our simulation, analysis and comparison prove that our proposed topology is valid and the stability analysis result is reliable [17]. Our design uses less devices and has high power density.

II. PRINCIPLE OF OPERATION

A. CONSTRUCTION METHOD

The loads of HAPs usually acquire energy from the bus. Certain loads, headed by the dynamic system, have high power consumptions and are not suitable to work with high power DC/DC converters. They usually take the bus voltage as the working voltage. To make them work at a rated voltage to improve the conversion efficiency, a regulated bus topology becomes a new option.

Currently, HAP energy systems with MPPT capability usually fall into two topology categories: unregulated and fully-regulated buses. The unregulated bus only has one DC/DC converter and is therefore used more frequently due to the convenience regarding control and high efficiency. Its disadvantage is that the bus voltage always follows the battery voltage. When there are large variations in system energy flows, the load efficiency becomes worse. The fully-regulated bus has three unidirectional converters – one additional battery charging regulator (BCR) and one additional battery discharging regulator (BDR), compared to the unregulated topology, thereby enabling a constant bus voltage. Some articles used a bidirectional converter to realize the function of BCR and BDR which doesn’t change the power flow count [18], [19]. However, during battery charging and discharging, the converter loss is higher. Schematics of the two topologies are illustrated in Figures 3 and 4.

We propose a novel semi-regulated bus topology consisting of two DC/DC converters and a diode, as schematically illustrated in Figure 5. In the daytime, the solar panels provide...
power to the loads and charge the battery simultaneously, during which the bus voltage is regulated. During the nighttime, when solar panels cannot work or when light is insufficient such that the loads need to be powered jointly from solar panels and the battery, the loads connect to the battery through the diode and its voltage follows the battery. The semi-regulated bus topology combines the advantages of fully-regulated and unregulated buses. Based on this topology, we further simplify the TPC design through multiplexing devices of identical functionality.

The dashed rectangles in Figure 5 are two identical sub circuits of inductor and switch in parallel. Through merging, we want to obtain a simplified TPC topology with device multiplexing.

The simplified circuit has one less inductor. However, when the solar panels power the loads and charges the battery simultaneously, the charging control is miss. That means an additional switch is needed to isolate battery from the path that solar panels power the loads to avoid disturbances. In addition, a buffering inductor $L_F$ is installed to prevent large current during mode switching and to maintain the voltage differences between the bus and the battery. To avoid voltage spike and release energy from $L_F$, a freewheeling diode $D_F$ is necessary when $S_2$ turn on. Since the impedance of $L_F$ is small, the impact on power density is minimal and it can be ignored in modal analysis. Furthermore, to minimize the conduction loss of $D_3$ while maintaining the functionality of the semi-regulated bus, we replace it with a MOSFET with a reverse diode. This MOSFET does not work at high frequency and therefore has no dynamic loss. The purpose is to reduce the conduction loss and to isolate the battery voltage from the regulated bus during mode switching. We also connect a switch in serial in the dashed rectangular to control battery charging. This new semi-regulated TPC topology is shown in Figure 6.

The battery charge control process is begun with a MPPT control which aims to maximum the charge power. When the battery voltage rises to a pre-established value, it comes to constant voltage charging mode and the current decreases with time. During the charging process, the current must not exceed over the set current limit. If the power is too large to charge the battery, the system working outside the MPPT mode but go to constant current charging mode.

There are four working conditions, their corresponding period is shown in Figure 7.

**Working Condition 1:** In the daytime with strong sunlight, the solar panels charge the battery through MPPT and supply the loads as a constant voltage source through the voltage stabilizing circuit.

**Working Condition 2:** In the daytime with weak sunlight, the loads need to be jointly powered by the solar panels and the battery. The output voltage is equal to the battery voltage. This is the working condition during the short period of sunrise and sunset.

**Working Condition 3:** During the night with no illumination, the loads are solely powered by the battery. The output voltage follows the battery voltage.

**Working Condition 4:** The battery is fully charged and the PV input power is fed to the loads. The output voltage is constant.

### B. STATIC ANALYSIS

We include three modes in the circuit modal analysis. In modes 2, both switches are open. If both $S_1$ and $S_2$ are closed, the current flows through $S_1$ and will not power the subsequent stages, which is same as mode 1. This is meaningless and should not be a valid working condition.
The working condition 1 is the most important state of the converter which includes all modes in Figure 8. This condition realizes both bus voltage regulated through Mode 1 and Mode 2 and MPPT through Mode 3 and Mode 4. The gate signals of S1 and S2 are interleaved with $180^\circ$.

In working condition 2, the MOS and S1 is working. Working condition 3 and 4 only has MOS and S1 working respectively.

**Mode 1** $[t_0-t_1]$: In this stage, S1 is open and S2 is turned off. Therefore, the inductor is charged by the input source from solar panels. C1 and C2 are discharging to supply output load and battery respectively. D1 and D2 are reversed-biased. S1 is controlled by PWM wave whose duty is only depended on output voltage.

**Mode 2** $[t_1-t_2]$: This stage is to supply output load through input source and L. S1 and S2 are turned off. D1 starts to transfer the energies of L and input source to the output while charging C1.

**Mode 3** $[t_2-t_3]$: In this stage, S1 is turned off and S2 is turned on. Therefore, inductor L is charged by the input source while D2 conducts to carry C2 and battery charge current. C1 starts to discharge for output load. S2 is controlled by PWM wave whose duty is depended on input parameters or charging mode.

**Mode 4** $[t_3-t_4]$: This stage is the same as Mode 2.

The main waveforms are illustrated in Figure 9.

For inductor L, the charging times are $t_0-t_1$ and $t_2-t_3$, corresponding to $D1T_S$ and $D2T_S$, during which the current through L increases and the voltage across L is equal to $V_{in}$ and $V_{in} - V_B$, respectively. We then have:

$$V_{in} = L \cdot \frac{dI_L}{dt}$$

$$V_{in} - V_B = L \cdot \frac{dI_L}{dt}$$

In modes 2 and 4, L discharges. The respective time interval is $1-D1T_S-D2T_S$, during which holds.

$$V_{in} - V_{out} = L \cdot \frac{dI_L}{dt}$$

According to the volt-second balance law, we have

$$\frac{V_{in}}{L} \cdot D_1T_S + \frac{V_{in} - V_B}{L} \cdot D_2T_S = -\frac{V_{in} - V_{out}}{L} \cdot (1 - D_1 - D_2)T_S$$

where, $D_I$ is the duty cycle of S1 and $D_2$ is the duty cycle of S2.

Combining the above equations, we obtain the following equation set, from which it can be observed that the battery-end voltage and the load-end voltage of the TPC can be independently adjusted through the duty cycles of the two switches.

$$\begin{cases} V_{in} = V_BD_2 + V_{out}(1 - D_1 - D_2) \\ V_B = \frac{V_{in} - V_{out}(1 - D_1 - D_2)}{D_2} \\ V_{out} = \frac{V_{in} - V_BD_2}{1 - D_1 - D_2} \end{cases}$$

When the loads are powered jointly by the solar panels and the battery, S2 is open and the output voltage is equal to the battery voltage. At this time, the functionality of S1 is to control the solar panels with MPPT. This is similar to the unregulated bus, where the load voltage follows the battery voltage.

**C. DESIGN CONSIDERATIONS**

In our proposed semi-regulated bus TPC network, if the solar panel voltage is noted as $V_{in}$, the load output voltage is noted
as $V_{out}$ and the battery voltage is noted as $V_B$, and if only the boost is used to implement the semi-regulated bus, there is:

$$V_{in} < V_B < V_{out}$$

(6)

According to the modal analysis, the semi-regulated bus TPC cannot work when the two switches are both closed and their phases differ by half of a period, so

$$D_1 \leq 0.5$$

$$D_2 \leq 0.5$$

(7)

We expect the proposed TPC to work in continuous current mode (CCM). Therefore, for the boost-based topology, the main inductor current should be continuous. Its ripple $\Delta I_L$ can be expressed as:

$$\Delta I_L = \frac{D_1 I_{in}}{T_s} = \frac{D_1 V_{in} T_s}{L}$$

(8)

where, $f_s$ is the switching frequency equals to $1/T_s$.

The input mean current equals to the inductor mean current $I_L$. To work in CCM mode, the input mean current should satisfy:

$$I_{in} = I_L = \frac{(I_B - I_{out} D_2) V_B}{V_{in}} + \frac{I_{out}}{1 - D_1 - D_2} \geq \frac{D_1 V_{in} T_s}{2L}$$

(9)

### III. STABILITY ANALYSIS

For the convenience of analysis, we simplify the battery as a resistor with an equivalent resistance of $R_B$ during charging.

In mode 1, S1 is closed and S2 is open and the inductor stores energy.

$$V_{in} = L \cdot \frac{d\hat{I}_L}{dt}$$

(10)

$$\hat{V}_B = -C_2 \cdot \frac{dV_B}{dt}$$

(11)

$$\hat{V}_{out} = -C_1 \cdot \frac{dV_{out}}{dt}$$

(12)

In modes 2 and 4, S1 and S2 are open and the inductor discharges through D1.

$$V_{in} = L \cdot \frac{d\hat{I}_L}{dt} + V_{out}$$

(13)

$$\hat{V}_B = -C_2 \cdot \frac{dV_B}{dt}$$

(14)

$$\hat{I}_L = \frac{V_{out}}{R_L} + C_1 \cdot \frac{dV_{out}}{dt}$$

(15)

In mode 3, S1 is open and S2 is closed and the inductor discharges through D2.

$$V_{in} = L \cdot \frac{d\hat{I}_L}{dt} + V_B$$

(16)

$$\hat{I}_L = \frac{V_B}{R_B} + C_2 \cdot \frac{dV_B}{dt}$$

(17)

$$\hat{V}_{out} = -C_1 \cdot \frac{dV_{out}}{dt}$$

(18)

The inductor mean voltage and the two capacitors’ mean currents over one period $T_S$ can then be computed as:

$$L \cdot \frac{d \langle i_L(t) \rangle}{dt} = \langle V_{in}(t) \rangle_{T_S} - (1 - d_1(t) - d_2(t)) \times \langle V_{out}(t) \rangle_{T_S} - d_2(t) \langle V_B(t) \rangle_{T_S}$$

(19)

$$C_2 \cdot \frac{d \langle \hat{I}_L(t) \rangle}{dt} = -\langle \hat{V}_B(t) \rangle_{T_S} + d_2(t) \langle \hat{I}_L(t) \rangle_{T_S}$$

(20)

$$C_1 \cdot \frac{d \langle \hat{V}_{out}(t) \rangle}{dt} = -\langle \hat{V}_{out}(t) \rangle_{T_S} + (1 - d_1(t) - d_2(t))$$

(21)

where, $d_1(t)$ and $d_2(t)$ are duty cycle as a function of time of S1 and S2.

Introducing state variables and small signal disturbances, including L current $\hat{i}_L(t)$, input voltage $\hat{V}_{in}(t)$, output voltage $\hat{V}_{out}(t)$, battery voltage $\hat{V}_B(t)$, S1 duty cycle $d_1(t)$ and S1 duty cycle $d_2(t)$. It can be obtained:

$$\begin{align}
\langle i_L(t) \rangle_{T_S} &= \hat{i}_L(t) \\
\langle V_B(t) \rangle_{T_S} &= \hat{V}_B(t) \\
\langle V_{out}(t) \rangle_{T_S} &= \hat{V}_{out}(t) \\
\langle V_{in}(t) \rangle_{T_S} &= \hat{V}_{in}(t) \\
d_1(t) &= D_1 + \hat{d}_1(t) \\
d_2(t) &= D_2 + \hat{d}_2(t)
\end{align}$$

(22)

Solving the small signal dynamic equations, we have:

$$L \cdot \frac{d\hat{I}_L(t)}{dt} = [V_{in} - (1 - D_1 - D_2) V_{out} - D_2 V_B]$$

(23)

$$C_2 \cdot \frac{d\hat{V}_B(t)}{dt} = \left( -\frac{V_B}{R_B} + D_2 I_L \right)$$

(24)

$$C_1 \cdot \frac{d\hat{V}_{out}(t)}{dt} = \left[ \frac{V_{out}}{R_L} + (1 - D_1 - D_2) I_L \right] - \hat{V}_{out}(t)$$

(25)

After eliminating the large signal terms and ignoring the multiplication of small signal terms, we obtain:

$$\begin{bmatrix}
\frac{d}{dx} \hat{i}_L(t) \\
\frac{d}{dx} \hat{V}_B(t) \\
\frac{d}{dx} \hat{V}_{out}(t)
\end{bmatrix} =
\begin{bmatrix}
0 & -\frac{D_2}{L} & \frac{1 - D_1 - D_2}{L} \\
\frac{D_2}{C_2} & -\frac{C_2 R_B}{C_1} & 0 \\
\frac{1 - D_1 - D_2}{C_2} & a_{32} & -\frac{1}{C_1 R_L}
\end{bmatrix}$$

(26)
FIGURE 10. AC small signal equivalent circuit of semi-regulated bus TPC.

FIGURE 11. System closed-loop control diagram.

\[
\begin{bmatrix}
\hat{i}_L(t) \\
\hat{V}_B(t) \\
\hat{V}_{out}(t)
\end{bmatrix}
= 
\begin{bmatrix}
\frac{1}{L} & \frac{V_{out}}{L} & \frac{V_{out} - V_B}{L} \\
0 & L & \frac{I_L}{C_2} \\
-\frac{I_L}{C_1} & -\frac{I_L}{C_1} & \frac{a_{31}}{C_1}
\end{bmatrix}
\begin{bmatrix}
\hat{V}_{in}(t) \\
\hat{d}_1(t) \\
\hat{d}_2(t)
\end{bmatrix} + 
\begin{bmatrix}
\hat{V}_{in} \\
\hat{d}_1 \\
\hat{d}_2
\end{bmatrix}
\] (26)

From these equations, three equivalent circuit models are obtained, the combination of which leads to an AC small signal equivalent model, as shown in Figure 10.

Transforming the equations into the frequency domain, we have:

\[
\begin{align*}
sL\hat{i}_L &= \hat{V}_{in} - (1 - D_1 - D_2) \hat{V}_{out} - D_2 \hat{V}_B + V_{out} \hat{d}_1 \\
+ (V_{out} - V_B) \hat{d}_2 \\
sC_1 \hat{V}_B &= -\frac{\hat{V}_B}{R_B} + D_2 \hat{i}_L + I_L \hat{d}_2 \\
sC_2 \hat{V}_{out} &= -\frac{\hat{V}_{out}}{R_L} + (1 - D_1 - D_2) \hat{i}_L - I_L \hat{d}_1 - I_L \hat{d}_2
\end{align*}
\] (27)

From which open-loop transfer functions can be deduced, where H11–H33 are the three independent open-loop transfer functions, respectively. A schematic incorporating the MPPT closed-loop control is shown in Figure 11.

Through the Mason formula, the closed-loop transfer function can be written as:

\[
\frac{\hat{V}_B}{\hat{V}_{in}} = H_{23} - \frac{H_{13}H_{MPPT}H_{22}}{1 + H_{12}H_{MPPT}}
\]

\[
\frac{\hat{V}_{out}}{\hat{V}_{in}} = \frac{H_{33}}{1 + H_{33}H_{CV}}
\] (28)

where the parameters can be expressed as follows: (30)–(34), shown at the bottom of the next page.

We validate the system stability through a set of experimental parameters used and obtain the $V_B$ gain Bode plots in working condition 1, as shown in Figure 12. It can be observed that the gain margin is large and the phase margin is $\sim 45^\circ$. The $V_{in}$ gain Bode plots is shown in Figure 13 which the phase margin is greater than 0$^\circ$. Therefore, we consider the system to be stable.

IV. EXPERIMENTAL VERIFICATION

A. SIMULATION RESULTS

We validate our proposal through simulations. The results of the input voltage of 200 V and fixed duty-cycle are illustrated in Figure 14. The phase difference between the rising edges of $D_1$ and $D_2$ is 180$^\circ$ and the values are 1/4 and 1/3, respectively. The resistances at the $V_B$ and $V_{out}$ ports are identical. The rated voltage of regulated bus is 300V. The overshoot of
output voltage is about 1.5 times of rated voltage while the regulating time is short.

We build our semi-regulated bus TPC system simulation platform with Simulink to simulate the working status of the solar panels and Li-ion battery. According to our high-altitude scientific balloon test, the number of Li-ion battery modules series-connected is 70. The solar panel is by modules connected in 2 parallel with 6 series components where the maximum power point voltage is 38.71 V.

The simulation parameters of each port are presented in Table 1.

Based on Table 1, through introducing independent MPPT and voltage stabilizing control, the simulation under various HAP working conditions can be carried out.

The simulated output voltage stabilizing process and MPPT process of working condition 1 are illustrated in Figure 15. The MPPT control algorithm adopts incremental conductance method to accelerate the tracking process. This method needs both input voltage and input current as parameters for computation which is suitable for highly reliable systems.

It is clear in Figure 15 that MPPT control reach stability before bus voltage regulated progress and the variable range...
of input voltage is more than 20V. This is because the step length is hard to determine which is affected by input voltage ripple and the time of MPPT. The larger the step length is, the wider the variable range will be. In order to realize high efficiency of power conversion, it is feasible to reduce the MPPT time by a relatively large step length.

In the simulation of working condition 2, the load power is increased to 4 kW. The output voltage stabilizing process and the MPPT process are illustrated in Figure 16.

To describe the function of $L_F$ which had been ignored in modal analysis, the current simulation of the converter is shown in Figure 17. At the moment of 0.02s, the circuit change from working condition 2 to working condition 1. It is clear that $L_F$ can suppress transient current while the D1 and D2 keep unchanged in a short time.

**B. EFFICIENCY MEASUREMENTS**

In our simulation model, the main losses are the switching loss and the conduction loss. The switching loss is incurred by the actions of switching MOSFETs. Although GaN devices have sound dynamic characteristics, the switching loss can still be amplified if the system’s working frequency is elevated. The conduction loss is mainly due to the internal resistance steady state loss when the device is conducting. The equivalent circuit of the TPC is showed in Figure 18 if we mark all non-ideal components separately. Where $r_L$ is the inductance internal resistance. $r_{S1}$, $r_{S2}$ and $r_{S3}$ are internal resistance of transistors. $V_{F1}$ and $V_{F2}$ are forward voltage of diode.

In Table 2, the main simulation parameters that impact efficiency are listed. All the non-ideal components are considered except internal resistance of capacitors.

In Figure 19, the efficiency as a function of D1 and D2 is illustrated. When $D1 = 0.5$ and $D2 = 0.5$, the system is under working condition 2 and the efficiency is 98.37%. All other valid efficiencies are under working condition 1. Since the converter cannot work when the two switches are closed at the same time, $D1 + D2 > 1$ is not computed. Due to the D2 affects how much power is charged to battery, the system will change working condition automatically when the charge power is large enough to lifting battery voltage higher than rated bus voltage. That’s the main reason for higher efficiency as one of the DC/DC in circuit is not working.

In Figure 20, the relationship between the output power and efficiency is illustrated with ground environment. When the
output power required by the loads exceeds 3500 W, the solar panel cannot supply by itself and the system transits from working condition 1 to working condition 2. There comes to a conclusion that efficiency raises with power increases.

C. EXPERIMENTAL RESULT

To verify the feasibility and rationality of the proposed TPC, we developed a prototype weighted 517g with frequency of 200 kHz and power density 5.291 W/cm$^3$. Figure 21 shows the experiment about the prototype and the relative infrastructures while the system working under 400W condition. The thermal design includes PCB design and external heatsink design which is shown in Figure 22. We increased copper area appropriately and fitted thermal pads for better thermal performance. The external heatsink is made of aluminum where the size of it is 35×40×23mm. The heatsink use trapezoidal structure to diffuse heat source.

The thermal imaging of the converter working under 350W is shown in Figure 23. Without the additional heatsink, the maximum temperature in this condition is from SiC diode which up to 52 °C.

Figure 24 shows the experimental results of the proposed TPC and the measurement been marked in it are maximum value. Figure 24a shows the experimental waveform of $V_{out}$ and $V_B$ in working condition 1. According to Figure 24b, the current of $L$ is showed which the average value equals to 2.82 A. Figure 24c is the waveform about voltage of $S1$ and $S2$. It is clear in Figure 24d that the freewheeling diode $D_F$ produce effect while $L_F$ is working.

D. CONVERTER COMPARISON

In recent years, the DC TPC has seen extensive usage in renewable energy systems. However, the investigation of TPC for HAP usage is still insufficient. All types of TPC have their advantages and shortcomings. Almost all TPC designs aim to reduce the number of energy storage devices since the weight of inductors and capacitors represents the largest percentage
of the switching circuit. In addition, apart from improving the power density, the reliability is also an important index of TPC performance. Reducing the number of switches and avoiding the usage of coupling inductors are the most direct means to improve reliability and an effective means to save the cost. In Table 3, the component counts and features of various TPC sources are compared. As can be seen that the proposed topology has both battery charge and MPPT function with semi-regulated bus function while there are fewer components resulting in higher efficiency.

### V. CONCLUSION

In this study, a non-isolated semi-regulated bus DC TPC topology has been proposed. The TPC combines the advantages of fully-regulated and non-regulated buses and is suitable for the usage in high-altitude platform energy systems. Our proposal uses less semiconductor devices and has high power density, efficiency and reliability. Firstly, through simulation and analysis, we prove the validity of our proposed topology. Secondly, we implement the topology with non-ideal components to simulate and analyze system stability and efficiency. Finally, through comparison, we conclude that our proposed semi-regulated bus TPC uses less components and is capable of achieve high integration, high efficiency and high reliability, thereby meeting HAP energy management needs.

### ACKNOWLEDGMENT

The authors would like to thank the International Science Editing for editing this manuscript.

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**Funding:**