Efficiency Optimization Method for Cascaded Two-Stage Boost Converter

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ABSTRACT A method of optimal intermediate voltage tracking (OIVT) is proposed in this paper to improve efficiency for the cascade boost converter. The intermediate voltage can be adjusted by regulating the duty cycle of front stage and rear stage converters. To improve the control speed of the algorithm, the intermediate voltage range is determined by calculating the overall system loss. In addition, with the input-output relationship maintained, the root-mean-square (rms) current of the intermediate capacitor can be reduced by changing the phase difference between front and rear side PWM signals. On this basis, a method of optimal phase-shift angle tracking (OPAT) is proposed to further improve efficiency for the system and extend service life for the capacitor through relatively simple implantation. Besides, the proposed OIVT and OPAT method is applicable to other cascade topologies. A 1-KW prototype is constructed in the laboratory to verify the proposed control method. As confirmed by the experimental results, the maximum efficiency reaches 95.23% when the proposed control method is adopted, which is 2% higher than under the uncontrolled condition. It is demonstrated that the proposed OIVT and OPAT method is effective in improving efficiency for the system without needing any additional components.

INDEX TERMS Capacitor current ripple, dc/dc power conversion, optimal phase-shift angle tracking, optimal intermediate voltage tracking, two-stage converters.

I. INTRODUCTION

Photovoltaic (PV) cell is one of the most important energy in the sustainable energy system. However, the voltage level of this source is too low and unpredictable unstable. In addition, the output voltage of the photovoltaic cell is changed with climate conditions. Therefore, converters with high voltage conversion ratio are essential in new energy resources system as shown in Fig.1 [1],[2]. A classical boost converter is widely used in these applications, but high conduction losses on the power devices and serious reverse recovery problems can be occurred under the extremely large duty cycle condition.

Although both transformer-based and transformer-less dc/dc converters can be applied in high voltage gain condition. The requirements in power density, weight, size and cost of the power devices make the transformer-less topologies to become a better choice [3-6]. In addition, voltage spike generated by the leakage inductance of the coupled inductor can not be neglected for transform-based converters.

FIGURE 1. Typical two-stage power-conversion system.

Cascade converters are adopted in many power systems to manage sources and loads at different voltage levels simultaneously. In terms of cascade boost converter, the voltage conversion ratio is high enough with low conduction loss on the power devices [7-9]. In addition, the cascade boost converter represents a good trade-off between efficiency and duty cycle operating range. A robust controller design to obtain output voltage regulation in a quadratic boost converter with high DC-gain is discussed in [10]. However, the implementation of the proposed hybrid control method is difficult to implement. In addition, the output power is only 100-W and it has not been verified at high power rating. A hybrid control method for the voltage regulation of conventional boost converter is presented in
The mathematical model and the control process are simple, but the implementation is difficult because many detect sensors and control elements are applied in the proposed control method.

Buck, boost, buck-boost, and Ćuk converters are analyzed and compared as dc–dc converters that can be cascaded in [12]. The buck and boost converters are shown to be the most efficient topologies for a given cost, while flexible in voltage ranges, buck-boost, and Ćuk converters are always at an accuracy in order or alternatively cost disadvantage. However, the voltage gain ratio and power ratio of the traditional topologies are relatively low. In addition, maximum power point tracking (MPPT) method is applied to many PV panels which is difficult to realize.

A generalized switching modification method is proposed in [13] to reduce the rms current flowing into a dc-link capacitor in a dc-dc-ac structure consisting of a boost converter and a three-phase inverter, the proposed method has a better capacitor rms current reduction performance in the mid-power factor level (0.95 to 0.1). However, the proposed method is hard to implement and the control accuracy is not guaranteed.

Kolar and Round [14] analyzed the current stress on the dc-link capacitor in a voltage PWM converter system. The paper focuses on a one-stage inverter system and states that the capacitor RMS current is determined by the load current. The bus capacitor ripple current of cascaded two-stage converters for dc systems is analyzed in [15], the capacitor RMS current value can be reduced without affecting the converter normal operation or the need for extra sensing circuits. However, the intermediate voltage is not considered and the proposed method is not verified under high power rating.

Lu et al. [16] propose a carrier modulation method to synchronize the dc/dc converter and sinusoidal PWM (SPWM) inverter in order to reduce the dc-link capacitor ripple current. This modulation method is only designed for an ac inverter to be the rear stage. Focusing on the three-phase back-to-back ac/dc/ac conversions, Gonzalez et al. [17] analyzed the dc-link current and proved that synchronizing PWM signals of the rectifier and inverter either in phase or antiphase would provide the lowest RMS current. This paper also only focuses on the ac/dc/ac topology and it is not suit for other topologies and dc-dc conversions.

The current and voltage ripple of a capacitor can be reduced by attaching an additional circuit composed of an energy storage element and a switch element to a dc-link capacitor in series or in parallel [18–22]. This method has the advantage of effective control of the power flow between the converters through the switching device and energy storage element. However, the cost and volume increase due to the additional auxiliary circuit, the complexity increases owing to additional control, and the ripple current generated due to the nonlinear characteristic of the switches cannot be reduced.

![Circuit diagram of the cascade boost converter.](image)

Some methods have been proposed in [23–26] in order to increase efficiency of the dc–dc converter, however, additional components are required in terms of these studies which increases the difficulty of design.

According to the literature presented above, the dc–dc converter applied to renewable energy should satisfy the following requirements.

1. The voltage conversion ratio is high enough in order to matching the dc-bus voltage.
2. The control method is simple and accurate in order to easy to implement.
3. The output power and efficiency of the overall system should be high enough.
4. The proposed control method is effective in improving efficiency without needing any additional components.

In order to solve the problems presented above. This paper focus on analyzing the influence of different intermediate voltage and phase-shift angles of two-stage boost converter. The intermediate voltage can be adjusted by regulating the duty cycle of the front stage and rear stage converters. In addition, the rms current of the intermediate capacitor can be decreased by changing the phase difference between the front and rear side PWM signals. Therefore, OIVT and OPAT control method are proposed to improve the system efficiency quickly and accurately and prolong the capacitor lifetime with relatively simple implantation. A 1-KW prototype was set up in the laboratory in order to verify the proposed control method. The results of the experiment confirmed that the maximum efficiency of the proposed control method is 95.23% which is 2% higher than the uncontrolled condition.

### II. OIVT AND OPAT METHOD OF THE CASCADE BOOST CONVERTER

#### A. VOLTAGE REGULATION METHOD OF THE CASCADE BOOST CONVERTER

Circuit diagram of the cascade boost converter is shown in Fig.2. \( V_{in} \) and \( I_{1,1} \) are the input voltage and current obtained from photovoltaic cell, \( V_o \) and \( I_o \) represent the output voltage and current, and \( V_m \) is the intermediate voltage of the cascade boost converter. Based on the operating principle of the cascade boost converter, under different intermediate voltage, the losses of each
component are different because of different voltage and current stresses. Therefore, it is difficult to derive the relationship between the intermediate voltage and the efficiency of the system because accuracy is not guaranteed by calculation. In order to solve this problem, an optimal intermediate voltage tracking (OIVT) method is proposed in this paper. The intermediate voltage can be adjusted by regulating the duty cycle $D_1$ of the front side converter boost1, the output voltage can be stabilized at 380V by regulating the duty cycle $D_2$ of the rear side converter boost2. The voltage gain ratio of the cascade boost converter can be given as

$$G_v = \frac{V_o}{V_m} = \frac{1}{1-D_1} \frac{1}{1-D_2}$$

The intermediate voltage can be calculated as

$$V_m = \frac{1}{1-D_1} V_o = (1-D_2)V_o$$

The inductor current ripple generates an inductor core loss $P_{\text{core}}$, which can be given as

$$P_{\text{core}} = \alpha \cdot f_{\text{sw}} \cdot \Delta B^2 = \alpha \cdot f_{\text{sw}} \cdot \left(\frac{\Delta L}{N \cdot A}\right)^2$$

where $\alpha$, $\beta$, and $\gamma$ are the coefficient values of the core, $B$, $I_L$, $L$, and $N$ are represent the flux density, inductor current, inductance and number of windings of the inductor. $f_{\text{sw}}$ is the switching frequency, and $A$ is the cross-sectional area of the core.

The current ripple of the front stage inductor $L_1$ and rear stage inductor $L_2$ can be expressed as

$$\Delta I_{L_1} = \frac{V_m \cdot D_1}{f_s \cdot L_1}$$

$$\Delta I_{L_2} = \frac{V_m \cdot D_2}{f_s \cdot L_2}$$

![FIGURE 3. Flowchart of the proposed OIVT method.](image)

From (3) and (4), the core losses are different under different intermediate voltage. In addition, copper losses of the inductors and other components are also varying with the intermediate voltage. Therefore, it is necessary to propose the optimal intermediate voltage tracking (OIVT) method for improving the efficiency of the cascade boost converter.

The flow chart of the proposed OIVT method is described in Fig.3. The detailed tracking process is shown as follow:

1) The initial dc input voltage $V_{in0}$ and intermediate voltage $V_{m0}$ are applied. $V_{m0}$ is applied within a reasonable range. The converters on the front side and rear side are automatically adjust duty cycle to generate the designated intermediate voltage and output voltage. In addition, the input power $P_{in0}$ is measured and recorded by the controller.

2) The intermediate voltage $V_m$ is then increased (or decreased) slightly to a new value $V_{m1} = V_{m0} + \Delta V_m$ ($V_{m1} = V_{m0} - \Delta V_m$). The duty cycle of boost1 and boost2 are forced to regulate the output voltage to 380V. The input power is measured and record as $P_{in1}$ under this condition.

3) Compare $P_{in1}$ and $P_{in0}$. When $P_{in1}$ is smaller than $P_{in0}$, then repeat step 2 ($V_{m1} = V_{m0} + \Delta V_m$) until the input power stops decreasing. Then, a maximum efficiency point is found. Otherwise, when $P_{in1}$ is larger than $P_{in0}$, the tracking direction is reversed, then repeat step 2 ($V_{m1} = V_{m0} - \Delta V_m$) until the input power stops decreasing and a maximum efficiency point is found.

4) After waiting the time interval $t_d$, a new tracking process is presented in case that the load and/or the input voltage $V_{in}$ have varied.

By applying the proposed control method, it is easy to find the optimal intermediate voltage value. Compared with the simulation methods proposed in [15], the proposed method is more accurate than the simulation method because of the real-time characteristic in terms of the tracking process.

The voltage control loop is shown in Fig.4, in terms of the output voltage $V_m$, the reference voltage $V_{m,\text{ref}}$ is set to 380V which is taken as a constant value, the reference voltage $V_{m,\text{ref}}$ is calculated from Fig.3 which is obtained from OIVT control method. The output voltage $V_m$ and intermediate voltage $V_m$ can be accurately controlled by adopting the voltage closed loop control.

From the above analysis, the system efficiency can be improved by applying the OIVT control method. However, the data processing speed is slow. From part III, the power loss can be calculated based on the polynomial taken $V_m$ as the variable. Therefore, the variation range of intermediate voltage can be calculated based on the function (16)-(23),

![FIGURE 4. Voltage control loop for the cascade boost converter.](image)
then the precise intermediate voltage can be obtained through OIVT control method rapidly.

**B. PHASE DIFFERENCE REGULATION METHOD OF THE CASCADE BOOST CONVERTER**

The efficiency of a system can be improved by applying the optimal intermediate voltage tracking method and the loss of power can be reduced by adopting OIVT. However, the intermediate capacitor as a component plays a vitally important role in the smooth operation of the two-stage boost converter. In addition, the service life and operating conditions of electrolytic capacitor can have a significant impact on the overall performance of the converter. According to [27], $T_{hot}$ is represented by the ambient temperature $T_{amb}$ and the capacitor ripple current denoted as $T_{hot}$ increases in accordance with the increase of root-mean-square (rms) current in the capacitor shown as below

$$T_{hot} = T_{amb} + R_{hs} \sum_{i=1}^{n} ESR(f_i) I_{rms}^2 (f_i)$$  \hspace{1cm} (5)

where $T_{hot}$ is the capacitor temperature under operation condition, $R_{hs}$ is the equivalent thermal resistance from hotspot to ambient, $ESR(f_i)$ is the equivalent series resistance at frequency $f_i$, and $I_{rms}(f_i)$ is the rms value of the ripple current at frequency $f_i$.

The equivalent circuits for different operation conditions are shown in Fig.5. According to the ON and OFF states of the two power switches $S_1$ and $S_2$, the current of the intermediate capacitor can be expressed as

$$i_{cm} = \begin{cases} i_{L2} & \text{if } S_1 \text{ ON} \\ i_{L1} - i_{L2} & \text{if } S_1 \text{ OFF} \end{cases}$$  \hspace{1cm} (6)

It can be inferred that both temperature and power loss can be reduced for the capacitor by reducing the rms current acting on the equivalent series resistance (ESR) of the capacitor. As for the cascade boost converter, the rms current of the intermediate capacitor is expressed as

$$I_{rms_{cm}} = \begin{cases} \frac{1}{T} \int_{0}^{T} (-i_{L2})^2 dt & \text{if } S_1 \text{ ON} \\ \frac{1}{T} \int_{0}^{T} (i_{L1} - i_{L2})^2 dt & \text{if } S_1 \text{ OFF} \end{cases}$$  \hspace{1cm} (7)

Power losses on the intermediate capacitor can be given as

$$P_{loss} = I_{cm_{rms}}^2 \times ESR$$  \hspace{1cm} (8)

Depending on the exact combinations of phase-shift between the two power switches, the overall operating principle can be divided into three modes, as shown in Fig.6. DT is the phase-shift time of the two PWM signals and $d$ is expressed as the phase-shift ratio. $K_{U1}$ and $K_{U2}$ denote the upstream slope and downstream slope of the corresponding inductor currents $I_{L1}$, respectively. The rms current of the intermediate capacitor is shown in (9)-(11). Based on (9)-(11), the current of capacitor RMS in the three modes is calculated and compared, as shown in Fig. 7.

![Diagram](image-url)
Regarding cascade boost converter, the rms current of the intermediate capacitor can be adjusted by regulating the phase difference of the duty cycle $D_1$ and $D_2$. In addition, the input and output relationship of the converter can be maintained even in the case of significant phase angle changes. Taking advantage of this feature, an optimal phase angle tracking (OPAT) method is proposed in this paper. Fig.8 shows the inductor current $I_{L1}$ and $I_{L2}$ and capacitor current $I_{cm}$ under different phase-shift conditions. It can be seen from this figure that as the phase angle changes for the inductor currents $I_{L1}$ and $I_{L2}$, the current of the intermediate capacitor varies accordingly. That is to say, the current of the intermediate capacitor can be changed by regulating the phase difference of the duty cycle $D_1$ and $D_2$. The flowchart is presented in Fig.9 and the tracking process is detailed as follows.
the decline of input power stops. Then, the optimal phase-angle point is determined.

\[
i_{cm(mode1)} = \begin{cases} \frac{-K_{1,I} t}{U_1} & \text{for } T_1 < t < T_2 \\ \frac{K_{1,I} t - K_{1,L} t}{U_1} & \text{for } T_2 < t < T_3 \\ \frac{-K_{1,I} t}{U_1} & \text{for } T_3 < t < T_4 \\ \end{cases}
\]

\[
i_{cm(mode2)} = \begin{cases} \frac{-K_{1,I} t}{U_1} & \text{for } T_4 < t < T_5 \\ \frac{K_{1,I} t - K_{1,L} t}{U_1} & \text{for } T_5 < t < T_6 \\ \frac{-K_{1,I} t}{U_1} & \text{for } T_6 < t < T_7 \\ \frac{-K_{1,I} t}{U_1} & \text{for } T_7 < t < T_8 \\ \end{cases}
\]

\[
i_{cm(mode3)} = \begin{cases} \frac{-K_{1,I} t}{U_1} & \text{for } T_8 < t < T_9 \\ \frac{K_{1,I} t - K_{1,L} t}{U_1} & \text{for } T_9 < t < T_{10} \\ \frac{K_{1,I} t - K_{1,L} t}{U_1} & \text{for } T_{10} < t < T_{11} \\ \end{cases}
\]

C. CONTROL METHOD OF THE CASCADE BOOST CONVERTER

Fig. 10 shows the block diagram of the proposed control method. As for the intermediate voltage range, it can be calculated according to part III for the improvement of control speed. Then, the optimal intermediate voltage is calculated and operated using the OIVT control method, while the intermediate voltage and output voltage are stabilized using the PI control method. In the meantime, the OPAT-enabled signal is started. Afterwards, the OPAT control method is applied. Since OPAT control method has effects only on the current of the intermediate capacitor, there is no conflict between the OPAT and OIVT control methods. The optimal phase-angle \( \theta \) can be adjusted using the OPAT control method, while the input and output power is calculated using the input output voltage \( V_{in} \) and \( V_o \), as well as the input output current \( I_{L1} \) and \( I_o \). With the proposed control method used, the optimal intermediate voltage and phase-angle can be determined in a fast and accurate way. In addition, the proposed tracking method is effective under different input and output conditions.

In addition, the proposed algorithm can be applied to other cascade topologies, such as cascade buck converter and cascade buck-boost converter, of which the former is applied at high current and low voltage while the latter is applied given a wide range of input and output voltage.

Table I shows the comparison performed between the proposed control method and other control methods. From the perspective of overall performance, the proposed method is clearly advantageous in efficiency, power rating and complexity. The stability criterion is the adjustment time and accuracy of the control method with the load variation. The complexity criteria are the number of devices and complexity of the control method.
TABLE I
COMPARISON BETWEEN THE PROPOSED METHOD WITH OTHER METHODS

| Performance         | Proposed method | Ref [28] | Ref [29] |
|---------------------|-----------------|----------|----------|
| Stability           | normal          | good     | good     |
| Complexity          | normal          | complex  | complex  |
| Components          | less            | less     | normal   |
| Efficiency          | high            | normal   | normal   |
| Power rating        | high            | low      | low      |

III. POWER LOSS ANALYSIS OF CASCADE CONVERTER

It is assumed that $R_{S1}$ and $R_{S2}$ are the resistance of the power switches $S_1$ and $S_2$, $V_{F1}$ and $V_{F2}$ are the threshold voltage of the power diodes $D_1$ and $D_2$. In addition, $R_{L1}$, $R_{L2}$ and $R_{C1}$, $R_{C2}$, $R_{Co}$ are the ESRs of the $L_1$, $L_2$ and $C_{in}$, $C_{M}$, $C_{o}$, respectively. The power loss model of the cascade boost converter is shown in Fig.11.

The power losses of the cascade boost dc-dc converter are mainly consisted by four parts: inductor loss, power switch loss, diode loss, and capacitor loss.

The copper losses of the inductors are given as

$$P_{Cu} = I_{L1(\text{rms})} \cdot R_{L1} + I_{L2(\text{rms})} \cdot R_{L2}$$

(12)

The rms current of inductor $L_1$ and $L_2$ are expressed as

$$I_{L1(\text{rms})} = \frac{P_m}{V_m}$$

$$I_{L2(\text{rms})} = \frac{V_m}{P_m} \cdot \frac{P_m}{R_m}$$

(13)

The ripple current of inductor $L_1$ and $L_2$ can be rewritten as

$$\Delta I_{L1} = \frac{V_m}{f_s \cdot L_1} \cdot (1 - \frac{V_m}{V_{in}})$$

$$\Delta I_{L2} = \frac{V_m}{f_s \cdot L_2} \cdot (1 - \frac{V_m}{V_{in}})$$

(14)

The inductor losses are calculated as

$$P_L = P_{Cu} + P_{r_{core}}$$

(15)

The core losses of the inductors are derived in (3) and defined as $P_{core}$.

The conduction losses and switching losses of the switches $S_1$ and $S_2$ can be calculated as

$$P_{SC} = R_{DS1} \cdot \left(1 - \frac{V_m}{V_{in}}\right) \cdot \left(\frac{P_m}{V_m} \right)^2 + R_{DS2} \cdot \left(1 - \frac{V_m}{V_{in}}\right) \cdot \left(\frac{P_m}{V_m} \right)^2$$

(16)

$$P_{SW} = \left(V_m \cdot \frac{P_m}{V_m} \cdot f_s + V_o \cdot \frac{P_m}{V_m} \cdot f_s \cdot \left(\frac{t_r + t_f}{2} + \frac{t_f + t_r}{2}\right)\right)$$

(17)

The capacitor losses are expressed as

$$P_C = P_{SC} + P_{SW}$$

(18)

where $t_r$, $t_f$, $I_{f1}$, and $I_{f2}$ are the voltage rise time, voltage fall time, current rise time, and current fall time, respectively.

The power losses in the diodes include the conduction losses and reverse recovery losses. The reverse recovery loss is neglected because the reverse recovery time in Schottky diode is very short.

$$P_D = V_{f1} \cdot \frac{P_m}{V_m} + V_{f1} \cdot I_o$$

(19)

The intermediate capacitor and output capacitor losses are calculated as

$$P_C = I_{CM(\text{rms})} \cdot R_{Co} + I_{Co(\text{rms})} \cdot R_{Co}$$

(20)

According to the efficiency definite above, the efficiency can be derived as

$$\eta = \frac{P_m}{P + P_L + P_C + P_S + P_D + P_{loss}}$$

(21)

The power losses under OIVT control method can be expressed as (19). From (19), $V_{in}$ and $P_o$ are treated as variables.

$$P_{loss} = P_L + P_S + P_D + P_C$$

(22)

The minimum power loss appears when the derivative of $V_{in}$ equal to 0.

$$\frac{\partial P_{loss}}{\partial V_{in}} = 0$$

(23)
According to the loss calculation results, the overall loss formula is expressed in (19), which is a function of intermediate capacitor voltage and output power, it is easy to analyze the overall efficiency under different $V_m$ and constant output power.

The efficiency of the overall system is calculated as shown in Fig12. From Fig.12, the optimal efficiency of the system is appeared at 600W, 130V. According to the calculated value, the intermediate voltage range can be achieved rapidly, the optimal intermediate voltage can be accurately obtained by OIVT control method.

The OIVT control method obtains the optimal intermediate voltage by calculating and voltage tracking process. OPAT control method contains the optimal phase difference by calculating and phase-shift angle tracking process with the input-output relationship maintained. The control time is shortened by calculation, the two control methods do not interfere with each other, and the optimal efficiency is obtained by adjusting the current and voltage stress of each component.

IV. EXPERIMENTAL RESULTS

In order to verify the performance of the proposed control method, a 1-KW prototype is constructed in the laboratory. The component parameters of the cascade boost converter are listed in Table II.

Silicon carbide power MOSFETs IRFP4137PBF and IPW60R280P6 are applied as $S_1$ and $S_2$. In addition, fast recovery diode HER3004C and IDW30G65C5 are used as $D_1$ and $D_2$. The dc electronic load serves as a resistance load. The efficiency is measured as the dc load power divided by the supplied dc power.

The (Equivalent series resistances) ESRs of the capacitors are denoted as $R_{cm}$ and $R_{co}$, as measured using the ESR meter at the operating frequency. The parameters of the semiconductors are obtained from datasheets.

The experimental waveforms of $I_L$, $V_m$, and $V_o$ at different dc input voltages are shown in Fig.13. According to the measurement performed at the minimum dc input voltage, the output voltage $V_o$ stabilizes at 380V when the proposed control method is used. In addition, Fig.13(a) shows the intermediate voltage $V_m$ =130V and $D_1$=0.63 when the OIVT control method is adopted. From the
experimental results shown in Fig.13(b), it can be found out that the intermediate voltage $V_m=120\text{V}$ and $D_f=0.5$ at the maximum dc input voltage when the OIVT method is applied.

Fig.14 shows the experiment results of $I_{L1}$, $I_{L2}$, $V_M$, and $V_s$ at different phase-shift angles. The phase-shift angle is adjusted to 150° using the proposed OPAT control method at the minimum input voltage, as shown in Fig.14(a). Differently, the phase-shift angle is adjusted to 120° using the proposed OPAT control method at the maximum input voltage, as shown in Fig.14(b).

![FIGURE 16. Measured capacitance temperature (a) with the proposed control method. (b) without the proposed control method.](image-url)

**TABLE II**

| Symbol | Parameter            | Value  |
|--------|----------------------|--------|
| $V_m$  | Input voltage        | 48-60V |
| $V_s$  | Output voltage       | 380V   |
| $L_1$  | Inductance of Boost1 | 150uH  |
| $L_2$  | Inductance of Boost2 | 780uH  |
| $C_m$  | Intermediate capacitance | 100uF |
| $C_o$  | Output capacitance   | 200uF  |
| $R_{on}$ | ESR of capacitor $C_m$ | 0.25Ω |
| $R_{on}$ | ESR of capacitor $C_o$ | 0.4Ω |
| $f_o$  | Operating frequency  | 50kHz  |

Fig.15 shows the transient waveforms of the proposed tracking algorithm from 500-W to 1-kW at different dc input voltages. According to Fig.15, given the maximum and minimum input voltages, as well as load variation, the output voltage maintains stability after transient adjustment made to the proposed OIVT and OPAT control method, which evidences the effectiveness of the proposed control method.

Fig.16 shows the capacitor temperature as measured under the controlled and uncontrolled conditions. As show in Fig.16(b), the temperature of the intermediate capacitor is $47°$ when the proposed control method is not used. From Fig.16(a), it can be seen that the measured temperature is $42°$ which means it is $5°$ lower under the controlled condition. These results demonstrate that using the proposed OPAT control method is effective in reducing the RMS current value of the intermediate capacitor without affecting the normal operation or needing additional sensing circuits for the converter.

![FIGURE 17. Calculated and measured efficiency of the proposed control method (a) under different intermediate voltage. (b) under different phase angle.](image-url)

**TABLE III**

| Efficiency improvement | Value |
|------------------------|-------|
| Maximum (OIVT)         | 1.35% |
| Minimum (OIVT)         | 1.22% |
| Maximum (OPAT)         | 0.4%  |
| Minimum (OPAT)         | 0.3%  |
| Average (OIVT)         | 1.25% |
| Average (OPAT)         | 0.35% |
The power loss analysis is conducted under the experimental conditions when $P_L=1$-KW. According to the analytical results of power losses breakdown as shown in Fig.18 (a), the power loss is determined as 65.3W when $V_{in}=48V$. Thus, it can be concluded that the major contributor to power loss is conduction loss, including the loss of switching devices and inductors. It accounts for 33% of the total losses. When the input voltage $V_{in}=60V$ as shown in Fig.18 (b), the power loss is calculated to be 47.7W. In this case, the major contributor to power losses is conduction loss, accounting for 30% of the total losses.

**IV. CONCLUSION**

In this paper, an analysis is conducted as to the effect of intermediate voltage and phase-shift between the duty cycle of cascade two-stage boost converter. A method of optimal intermediate voltage tracking (OIVT) is proposed in this paper to improve efficiency for cascade boost converter. The intermediate voltage can be adjusted by regulating the duty cycle of front stage and rear stage converters in a fast and accurate way. In addition, a method of optimal phase-shift angle tracking (OPAT) is proposed to further improve efficiency for the system and extend service life for the capacitor through relatively simple implantation.

A 1-KW prototype is built in the laboratory to verify the proposed control method. According to the experimental results, the maximum efficiency reaches 95.23% when the proposed control method is used, which is 2% higher than under the uncontrolled condition. Therefore, the proposed control method is effective in significantly improving the overall efficiency for the system. The model and analysis presented are of generic nature and thus applicable to most of the existing cascaded two-stage converters.

In the future work, in terms of the control method, the current and voltage acquisition process need to be simplified, and the angle calculation needs to be more accurate. Moreover, the control method proposed in this paper needs to be extended to the inverter in the future.

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