# Design Optimization of Planar Transformer for Bi-directional Forward Converter in Active Cell Balancing Applications

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## ABSTRACT

The bi-directional forward converter is one of the popular topologies suitable for battery cell equalizers. Although various analysis and design guidelines have been introduced, the transformer design is normally optimized for only uni-directional operation. This paper aims at optimizing the bi-directional forward converter considering both forward and reverse power transfer efficiency. Furthermore, the planar transformer is employed to reduce the volume of the equalizer which results in a power density increment. Both traditional and planar transformers are simulated on Ansys Maxwell under the same condition for a fair comparison. The simulation results show the volume of the planar transformer is only 31.8% of the conventional converter while the loss is 74.4% lower.

**Keywords:** Ansys Maxwell simulation, bi-directional converter, planar transformer, transformer design optimization.

## 1. INTRODUCTION

In general, hundreds of battery cells are connected in series inside the battery pack of the electric vehicle and the energy storage system. Due to the dissimilar cell characteristics during the aging, the over-charging and over-discharging issues can occur although the battery cells are operated under the same conditions [1]. Currently, the battery equalizer is the most effective solution for the performance mismatching of the cells. Various equalization methods have been introduced in [2], where the techniques are classified into passive and active catalogs. Among them, the passive balancing method within resistors to dissipate the battery redundant energy is more common in the battery industry. However, the resistor equalizer dissipating redundant energy creates energy loss in the system. Therefore, the combination of a switch-matrix and one converter is the most promising method in terms of reducing energy loss and balancing speed. The converter transfer the energy between cells to the battery pack, and vice versa. Since the battery cells are connected in series, the isolated converter is required to prevent the short circuit. The two-switch forward converter is a good candidate due to its simple structure and low switch voltage stress [3].

Although the design guideline for the forward converter is existing, only the uni-directional operation of the converter is analyzed [4]. Especially for the battery application, the operation of the converter is quite different than is required for the other applications. Similarly, the design of the transformer in the converter has been only optimized for one operation direction. Actually, there is a trade-off between the buck and boost modes in terms of efficiency and duty control. Thus, the turn ratio of the transformer should be carefully chosen to ensure high efficiency during both forward and reverse operations. On the other hand, the microcontroller unit (MCU) has a critical limitation in the resolution of the PWM modulation. Practically, the PWM duty becomes unstable when the duty is less than about 15%. Besides, the maximum duty cycle of the primary side of the forward converter should be less than 50% to prevent the saturation of the transformer. In the bi-directional operation, there is a middle duty point, which decides the direction of the

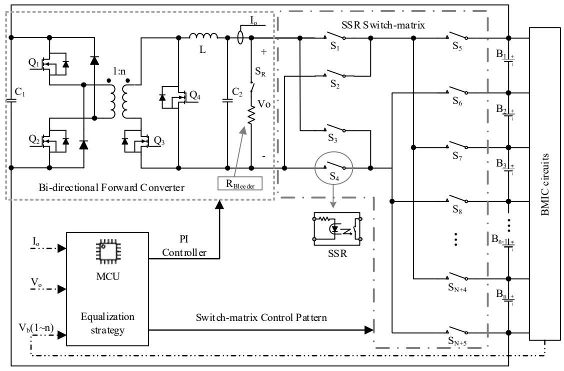



*Fig. 1*: *Battery cell balancing system consisting of bi-directional forward converter and switch-matrix*

energy flow. Thus, the turn ratio of the transformer should be optimized to adapt to all these requirements.

Meanwhile, the high density and low profile of the equalizer are required due to the small available space inside the battery pack. Since most of the circuit volume is occupied by the magnetic components, the planar transformer is preferable to the conventional transformer.

In this paper, the design optimization of the planar transformer for the bi-directional converter is investigated to reduce the power loss and the circuit volume. The relationship between the circuit design parameters and the performance indices is analyzed in Section 2. The performance comparisons between the conventional transformer and the planar transformer are summarized in Section 3. Finally, the conclusion is made in Section 4.

## 2. OPTIMAL OPERATION POINT SELECTION

### 2.1 Circuitry configuration

The equalizer consists of a bi-directional two-switch forward converter and a switch matrix as Fig. 1. By controlling the switching pattern of the matrix, one cell in the string is chosen to dock to the low side of the converter. The high side of the converter is connected to two end terminals of the battery pack. Thus, energy can be exchanged between the cells to the pack and vice versa. Based on the battery voltages, which are measured by a BMIC network, the switching pattern of the switching matrix is decided, and the converter is controlled by a PI controller.

### 2.2 Turn ratio consideration

In buck mode or pack to cell operation, the converter charges the weak cell by the battery pack. On the other hand, the cell is discharged to the battery pack during the boost mode. The voltage gain of the buck and boost modes are respectively calculated by

$$A_{Buck} = \frac{D}{N} \quad (1)$$

and

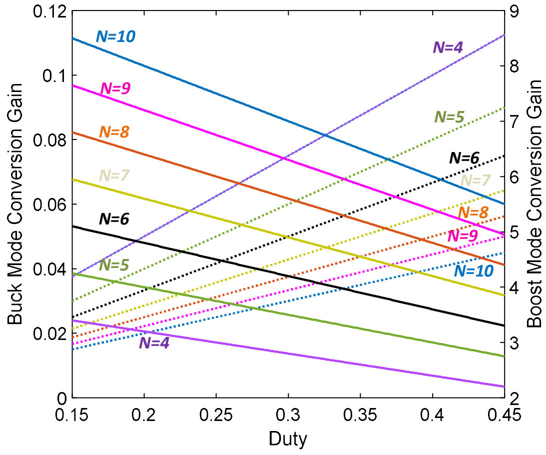



***Fig. 2***: *Voltage conversion gain vs. duty and turn ratio*

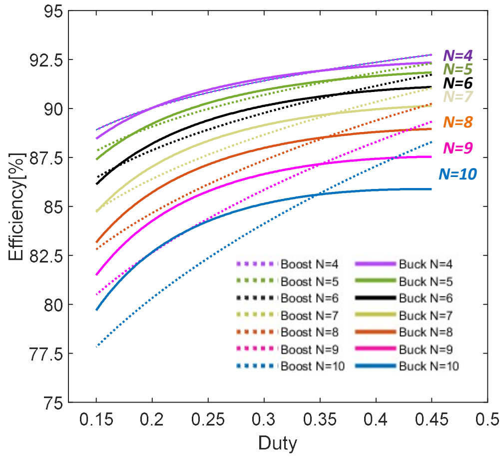



***Fig. 3***: *Efficiency vs. duty and turn ratio*

$$A_{Boost} = N(1-D) \quad (2)$$

where $A_{Buck}$ is voltage gain of buck mode, $A_{Boost}$ is voltage gain of boost mode.

According to the analysis in [5], the converter efficiency is expressed by

$$\eta = \frac{P_{in} - P_{cond} - P_{sw} - P_{diode} - P_{ind} - P_{cap} - P_{trfm}}{P_{in}} \quad (3)$$

where $P_{in}$ is input power of converter, $P_{cond}$ is conduction loss, $P_{sw}$ is switching loss, $P_{diode}$ is diode loss, $P_{ind}$ is inductor loss, $P_{cap}$ is capacitor ESR loss, and $P_{trfm}$ is transformer loss.

The converter is designed for a 20S1P battery module, and the circuit parameters are summarized in Table 1. Fig. 2 shows the voltage gain for duty and turn ratio. When the duty increases, the buck mode voltage conversion ratio decreases while the boost mode voltage conversion ratio increase. The efficiency of the bi-directional converter is plotted based on duty ratios and turn ratios in Fig. 3. The efficiency of each mode is different on the duty. Vividly, both the turn ratio of the transform and duty ratio of the PWM signal strongly affect the voltage gain and conversion efficiency. If the efficiency in the buck mode is preferred, the efficiency in the boost mode becomes poor and vice versa. To achieve high performance in both operation modes with at least 85% efficiency, turn ratios 4, 5, 6, or 7 can be considered as shown in Fig. 3. However, after considering the duty limitation for PWM operation of MCU, each mode needs to have a duty of at least over 10%. According to Fig. 2, the turn ratios satisfying the above duty margin condition are 6 or 7, and turn ratio 6 is finally chosen for its higher efficiency. Thus, the optimal turn ratio and the center of the duty are designed as 6 and 26%, respectively. It means that the boost mode is operated when the duty is in the range of 15%~26% while the buck mode is activated in the duty range of 26%~45%.

***Table 1:*** *Forward converter specification*

| | |
|---|---|
| Maximum Input Voltage $V_{i,max}$ | 84V |
| Minimum Input Voltage $V_{i,min}$ | 52V |
| Output Voltage $V_o$ | 4.2V |
| Output Current $I_O$ | 4A |
| Duty $D$ | 0.15~0.45 |
| Switching Frequency $f$ | $50kHz$ |

## 3. PERFORMANCE VERIFICATION

### 3.1 Simulation Setup

To compare the two different types of transformers in the view of the core loss and the energy density, transformers designed based on Table 2 are modeled on Ansys Maxwell. The coil diameter of the conventional transformer is designed to be 0.5mm for the primary wire and 0.7mm for the secondary wire. To decrease the simulation time, the curved surface of the coil is divided into 12 segments.

The coil width of the planar transformer is chosen to be 0.3mm for the primary wire and 1.5mm for the secondary side to prevent skin effect. And the distance between lines in the same winding was designed over 0.2mm. Last, the distance between lines in different winding is designed by $200\mu m$ to $400\mu m$ based on IEC 950 Safety Specification [6].

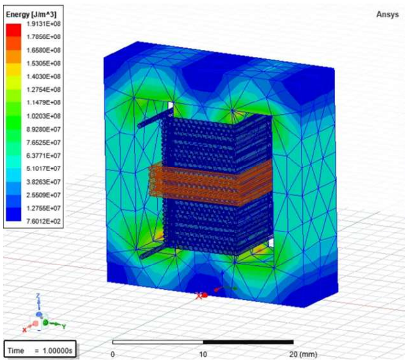
### 3.2 Simulation Result

Energy density is simulated on the transient solver of Ansys Maxwell with 84V voltage applied to the primary terminal and with $1\Omega$ load connected to the secondary terminal. The highest energy density of the conventional transformer is $1.9131 \times 10^8 J/m^3$ and the lowest is $7.6012 \times 10^2 J/m^3$. The highest energy density of a planar transformer is $7.5421 \times 10^7 J/m^3$ and the lowest is $1.6214 \times 10^2 J/m^3$ as shown in Fig. 4. The planar transformer shows almost 2 times the lower energy density than the conventional transformer.

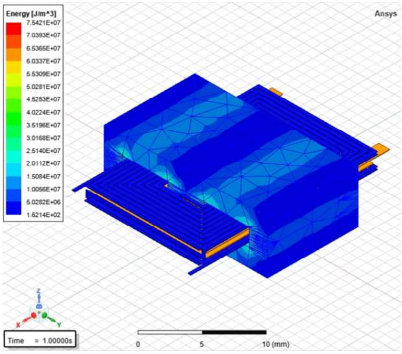
As shown in Fig. 5, core-loss density is simulated on the eddy current solver of Ansys Maxwell with the same condition. The highest core-loss density of a conventional transformer is $1.7421 \times 10^6 W/m^3$ and the lowest is $4.8217 \times 10^3 W/m^3$. The highest core-loss density of planar transformer is $2.9295 \times 10^6 W/m^3$ and the lowest is $1.0864 \times 10^3 W/m^3$.

***Table 2:*** *Transformer core specification*

| Transformer Type | Conventional | Planar |
|---|---|---|
| Core Selection | Ferrite N87 E25/13/7 | Ferroxcube E18/4/10 3C90 |
| Initial Permeability | 2200 | 2300 |
| Relative Permeability | 1620 | 1560 |
| Effective Volume $(mm^3)$ | 3020 | 960 |
| Effective Cross Section Area $(mm^2)$ | 52.5 | 39.3 |
| $B_{sat}(mT)$ | 490 | 470 |
| Height $(mm)$ | 25.6 | 6 |

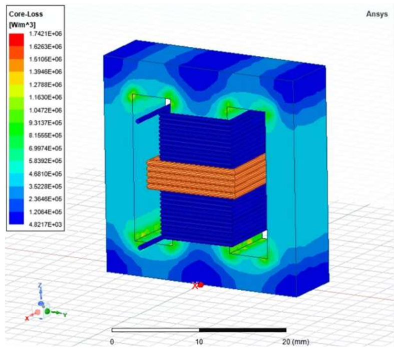


(a)

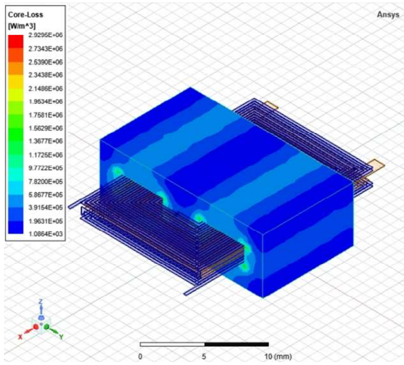


(b)

***Fig. 4**: Transformer energy density simulation: (a)Conventional transformer, (b)Planar transformer*



(a)



(b)

***Fig. 5:** Transformer core-loss density simulation: (a) Conventional transformer; (b)Planar transformer*

Although the planar transformer shows almost 1.5 times higher core-loss density than the conventional transformer, after considering overall volume, the total core loss of the planar transformer is $318.6mW$ and the total core loss of the conventional transformer is $1.245W$. Therefore, the core loss of the planar transformer is only 25.6% of the core loss of the conventional transformer.

## 4. CONCLUSION

This paper introduces the design optimization of a planar transformer for the bi-directional forward converter. By calculating the voltage gain and efficiency, optimal operation point selection of bi-directional converter is presented and planar transformer is designed accordingly. For the verification purpose, field simulation is performed by Ansys Maxwell software, which the benefit of the planar transformer approach by reduction of 76.6% in height, 68.2% in core loss, 74.4% in volume, and a higher power density than the conventional transformer. Thus, it is expected that the new design method can achieve high efficiency and miniaturize the active cell balancing circuit within battery packs.

## ACKNOWLEDGMENTS

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