Multi-Objective Design Optimization for PCB Transformer in Bi-directional Converters

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ABSTRACT

Adopting planar magnetic components with PCB windings is an attractive way to reduce the profile, volume, and weight of power converters. Specifically, when it comes to battery cell balancing applications, the design of the planar transformer encounters new challenges: the extreme voltage level difference between the primary and the secondary side and the bi-directional power flow operation. In this application, the buck mode operation and the boost mode operation frequently alternate to charge and discharge battery cells and the input and output voltage varies slowly but widely, which makes the conventional single-point design less effective. To mitigate such a complex issue, this paper introduces a multi-objective optimization procedure. The proposed method is applied, as an example, to the design of the planar transformer of the bi-directional forward converter in active cell balancing converters. The results draw various design candidates in view of the transformer volume, power loss, and temperature rise with a tradeoff relationship between the optimized solutions.

Keywords: Bi-directional converter, Finite element method, multi-objective optimization, planar transformer.

1. INTRODUCTION

For the active cell-balancing circuit inside the battery pack, the design bi-directional operation of the converter that operates as a charger distributor is different from the normal converter. 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 bi-directional operation. The volume of the equalizer should be compact to fit into the battery management system. In this case, planar transformers with printed circuit board (PCB) windings can be a viable choice in terms of optimization of low profile, lower volume, and high power [1].

During the design process of the planar transformer, multiple criteria such as the number of layers, the number of windings, and the width of the foil must be considered shown in Fig. 2. However if the transformer is only optimized for the small core volume, the winding loss and the temperature rise will not be optimized. Through this, it can be seen that the three penalty functions such as core volume, power loss, and the temperature rise of the planar transformer are related to each other as trade-offs, and the different aspects must be considered together to achieve the optimal design. Therefore, a multi-objective optimization technique is required to get an optimal planar transformer. Generally, the core volume is regarded as the most important factor that decides the whole profile of the PCB transformers. Besides, transformer loss is also a crucial factor in small power applications that affects the temperature rise.

In this paper, the multi-objective optimization of the planar transformer is adopted to reduce the core volume, transformer loss, and transformer temperature rise for the bi-directional converter. A brief review of the NSGA-II algorithm and multi-objective optimization procedure are described in Section 2. The optimization results by MATLAB and verification through Ansys Maxwell are summarized in Section 3. Finally, the conclusion is made in Section 4.

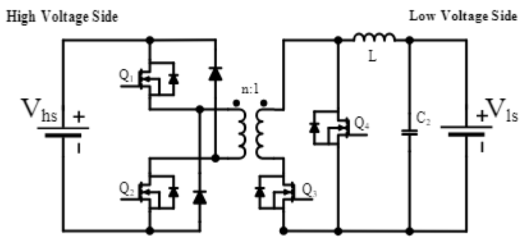

Fig. 1: Bi-directional forward converter used in the active cell equalizer inside the battery pack [2]

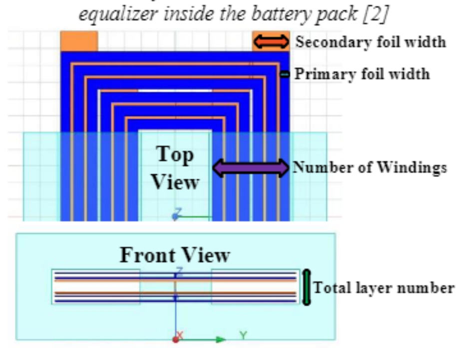

Fig. 2: Design parameters of the PCB transformer considered in this paper

2. MULTI-OBJECTIVE OPTIMIZATION

2.1 NSGA-II Algorithm

The Non-dominated sorting genetic algorithm-II (NSGA-II) performs optimization operations on variables in the population. By the fitness assessment, the algorithm increases the probability of being selected to the non-dominated front for well-evaluated variables. After the fitness assessment, the variables to be transferred to the next generation are selected, and discard unselected variables until the number of variables reaches the selected population. And generates a new generation that exceeds the selected population through crossover and mutation operations. Again, the algorithm performs the fitness assessment on a new generation. The optimization operation repeats up to a selected generation limit [3].

In NSGA-II, the first element to be selected as a parent object for generating the next generation is non-dominated front information. The non-dominated front is an important element representing the elitism of an object, and the higher the order of the non-dominated front, the greater the probability of reproduction to the next generation. The second factor is calculated as the concept of Euclidean distance between two entities for the objective function as cluster distance, and the greater the average cluster distance, the greater the diversity. For these reasons, the NSGA-II is chosen as an optimization algorithm in this paper.

2.2 Optimization Procedure

For illustration purposes, the algorithm is developed for the bi-directional forward converter in Fig. 1, which is frequently used as part of the battery cell balancing circuit. During the bi-directional operation, the turn ratio of the transformer takes a strong impact on the performance of the forward converter. In [2], the application of forward for the battery equalizer is analyzed. By considering both efficiency and duty control, the chosen turn ratio of the transformer is designed to be 6-to-1.

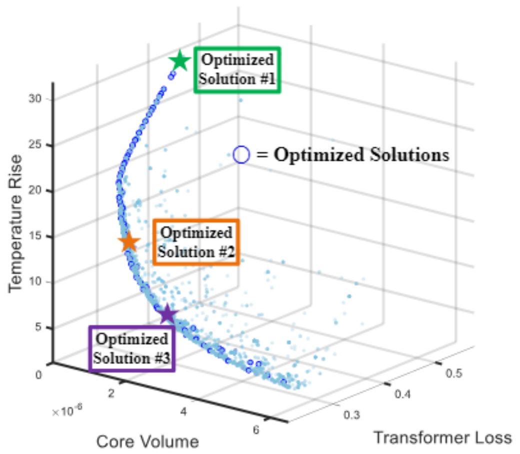

Fig. 3: Pareto-front plot of the solution candidates for the PCB transformer design

For objective function #1, transformer core volume is used which is decided by total layer numbers and foil width of the primary winding and the secondary winding.

Transformer loss is chosen for objective function #2, which consists of core loss and copper loss. For core loss, the Steinmetz equation is used [4], which is described as;

$$P_{core} = C_m \cdot f^x \cdot B_{peak}{}^y (ct_0 - ct_1 T + ct_2 T^2) \qquad (1)$$

where f is frequency, B_{peak} is peak-to-peak flux density, T is temperature, and C_m, ct_0, ct_1, ct_2, x, y are the Steinmetz coefficients from the manufacturer.

For copper loss, Dowell's formula for all the harmonics h is used [5], which is described as;

$$P_{cu} = R_{dc} \cdot \sum_{h=1}^{\infty} (k_{ph} I_h{}^2) \qquad (2)$$

where Δ_p is the penetration ratio, m is the number of layers in the coil, and k_p is the ratio between R_{ac} and R_{dc} which is the ac and dc resistance of the foil.

The transformer temperature rise for the convective heat transfer equation is used for objective function #3, which is described as;

$$\Delta T = \left(\frac{P_{transformer}}{A_s \cdot h_{coef}}\right) = R_{therm}(P_{core} + P_{cu}) \qquad (3)$$

where $P_{transformer}$ is the total power loss of the transformer, A_s is the surface area, h_{coef} is the heat coefficient for heat transfer and R_{therm} is the thermal resistance.

The foil width of the planar transformer is carefully chosen to prevent skin effects and the distance between lines in the same winding was designed over 0.2mm, and the distance between lines in different winding is designed from 200μm to 400μm based on IEC 950 Safety Specification.

Table 1: Solution candidates for the optimal design

Solution #	#1	#2	#3
Selected Population of NSGA-II	200		
Selected Generation of NSGA-II	100		
Turn Ratio	Primary:Secondary = 6:1		
Total Layer Number	14	8	5
Primary Foil Width (mm)	0.405	0.58	2.892
Core Volume (mm^3)	984	2096	4627
Transformer Output (W)	11.216		
Transformer Loss (W)	0.39	0.24	0.23
Temperature Rise (℃)	31.02	11.16	5.78

Table 2: Ansys simulation results for the solution candidates

Solution #	#1	#2	#3
Core Type in Market which Closes to Optimized Solution	E18/4/10	E22/6/16	E32/6/20
Core Volume (mm^3)	960	2100	4560
Transformer Loss (W)	0.4846	0.2115	0.1949
Temperature Rise (℃)	30.35	6.60	3.08

3. SIMULATION & VERIFICATION

3.1 Multi-Objective Optimization in MATLAB

NSGA-II optimization is implemented in MATLAB, and the result is illustrated in Fig. 3. Based on the solution distribution, three optimized solutions were selected and then further compared in the Ansys Maxwell simulation, which has an acceptable mounting area. Such solution candidates are optimized in terms of different aspects: Solution #1 is only for minimizing the core volume; Solution #2 is for considering the core volume and power loss, and Solution #3 is only for minimizing the transformer loss. Since the core volume is provided discretely due to the off-the-shelf core numbers, the solutions are calculated based on the existing products in the market.

3.2 Verification by Ansys Maxwell

The three optimized solutions were simulated in the Ansys Maxwell and the results are in Table 2. They clearly show a trade-off relationship between the core volume, transformer loss, and temperature rise. Transformer loss and temperature rise increase sharply as the volume decreases. In contrast, when the volume increase, the transformer loss decreases, but there is no significant difference between Solution #2 and #3. It is because the core loss also increases as the core volume increases.

Eventually, as a compromised solution among the core volume, transformer loss, and temperature rises, Solution #2 is recommended for the bi-directional converter as the most optimized design because all objective functions can be minimized within a practically feasible value in this paper.

4. CONCLUSION

This paper introduces the multi-objective optimization of a planar transformer using the NSGA-II algorithm. As a use case, the developed algorithm is applied to a bi-directional forward converter employed in battery cell balancing applications. By calculating the Pareto-front for the 3 objective functions - core volume, transformer loss, and temperature rise of the PCB transformer in the converter under design, optimal design for the planar transformer is made possible. Ansys simulation further proves the trade-off relationship between objective functions and diversity of selection can meet the performance in terms of design priority.

ACKNOWLEDGMENTS

This research was financially supported by the Ministry of Small and Medium-sized Enterprises(SMEs) and Startups(MSS), Korea, under the "Regional Specialized Industry Development Plus Program(R&D, S3088812)" supervised by the Korea Institute for Advancement of Technology(KIAT).

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