Feasibility Study About Design Process of Power Electronics Converters by Optimization Method Applied Machine Learning

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Applying the optimization methods to design for products as optimization problems is increasingly spreading. Since these methods can make design processes more efficient, we should also use them when designing power electronic converters. Design processes for power electronics converters are roughly classified into electrical circuit parameters, geometric properties of parts, and alignment of parts. These processes are studied as optimization problems individually and are combined into a series of design processes. However, since they are not strictly independent, solutions with low manufacturability may be derived. Therefore, the design process becomes inefficient because of the iterative calculations to get manufacturable solutions. In this paper, to reduce the iterative calculations, we propose the design process that simultaneously solves two of the above three optimization problems, electrical circuit parameters, and geometric properties of parts. On the other hand, calculation time for simulations becomes longer, so we substitute the machine learning model for simulations. The feasibility of the proposed process was validated through the design for a wireless power transfer system. Because of the machine learning model, the calculation time was reduced by 70%, and the range of designs could be expanded by 1.5 times.

1. Introduction

Momentum of regarding the global environmental problem of target 7 of the SDGs as important increases[1] worldwide, and it is necessary to suppress the loss at the time of energy conversion in power converters toward the achievement of the target. The Japanese government also positions this as one of the action plans[2], and our company is approaching through energy-related products, such as FA power supply, servo driver, and power conditioner. In addition, the change of social conditions represented by IoT and smart grid[3] allows a wide variety of electric appliances to be commercialized, and demand increases for power electronics converters that are necessary to operate those. Therefore, the miniaturization and higher efficiency of power electronics converters will be strongly required hereafter.

In recent years, the design and development of products are defined as an optimization problem, and the technology for obtaining results by numerical analysis is spreading[4]. The optimization problem is to obtain the minimum or the maximum condition from the set of values satisfying the function or condition defined in a certain real number space. This is applied to the design field of engineering to obtain the design value that maximizes arbitrary performance. In this paper, this is called the optimization process. The advantage is a point where the higher efficiency of design can be achieved. Many variables exist in design, and complicated tradeoff relations are recognized between characteristics. Therefore, a design capable of obtaining the target characteristic is not easy, and higher efficiency of the optimization process is estimated[5].

In the design of power electronics converters, the scene in which the optimization process is applied can be roughly classified into three types as shown in Table 1. The first is the study of the ideal characteristic value in which electrical circuit parameters, such as electrical circuits and LCR of the equivalent circuit, are obtained[6]. The second is the study of the feasibility of each part in which the geometrical properties of parts, such as magnetic parts and heat radiators , are determined so that the characteristic of the target is shown[7]. The third is the study of assembly in which the alignment of parts, printed circuit boards, and art work are designed[8]. These are reported in research cases

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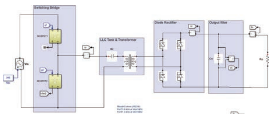
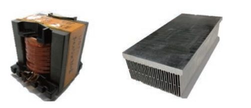
as optimization problems. Then, the combination of three types of problems constructs a series of design processes. However, since each problem is not independent, there is a possibility that the solution of low feasibility from the manufacturing aspect is derived in the flow in which they are executed in the order as they are. Thus, the phenomenon (loop) in which a solution is required repetitively is generated to heighten feasibility, resulting in inefficiency.

Table 1 Optimization Problem in Design of Power Electronics Converters[9,10)]

Decision parameters	Outline of optimization problem	Usecase
Electrical circuit parameters	Obtain electrical circuit parameter that minimizes loss of electrical circuit	
Geometric properties of parts	Obtain geometrical properties of parts capable of showing desired physical characteristics such as electromagnetism and thermal resistance	
Alignment of parts	Obtain alignment of parts that minimizes total size considering thermal performance, electromagnetic field and geometrical constraints	

This paper proposes a process for simultaneously studying two types of electrical circuit parameters and geometrical properties of parts among three for the purpose of reducing the loop. Since the third parts alignment is one of the causes of loop generation, it is preferrable to incorporate this at the same time. However, it requires a high degree of technical difficulty to set the proper model capable of evaluating the mutual interference of heat or the electromagnetic field between parts in this stage. In addition, since the increase in parameters leads to a wider design space, a problem arises in the convergence of the solution. Therefore, we will first study the process for simultaneously designing the former two. On the other hand, since this increases the calculation time of simulations to be used in the solution process, the increase in the time is suppressed by using the machine learning model. In order to verify the feasibility of these proposed design processes, the wireless power transfer system (WPT) that is one of power electronics converters was applied as an example.

2. Two-Stage Type Design Process to Be Proposed

2.1 Flowchart of Optimization Process

The design process of power electronics converters will be constructed by combining multiple optimization processes. Here we describe the optimization process that is the base. Fig. 1 shows its flow chart. Since a solution by numerical analysis is performed, we first perform the definition of problems based on the design purpose and its variables. Design variables are selected according to the magnitude of the degree of contribution to the characteristic and the correlation between variables and defined as decision variables. Various designs are produced by setting different values in these decision variables. In addition, in order to evaluate each design, its physical characteristic value is derived. In the case of power electronics converters, physical characteristics to be considered are the electrical circuit, control, magnetism, thermal fluid dynamics, and EMC (electromagnetic field). The evaluation value is calculated based on the obtained characteristic value, and updating of the variable value and design is repeated according to the optimization algorithm.

Three types of these optimization processes exist as shown in Table 1, and we will study the design process of power electronics converters by combining these in the next subsection.

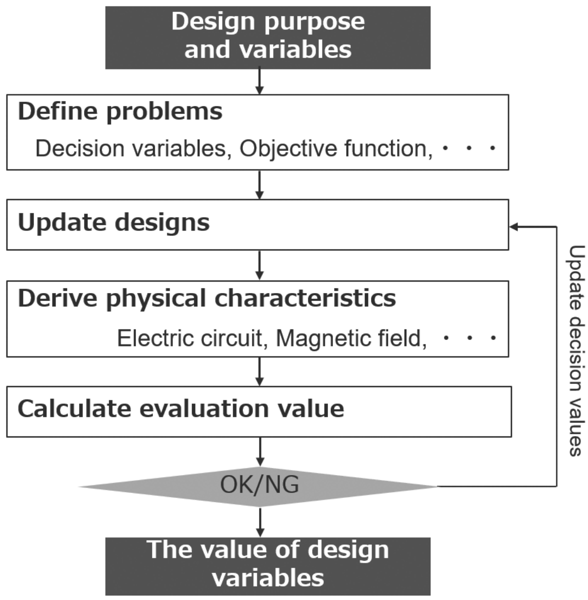


Fig. 1 Flowchart of Optimization Process

2.2 Problems of Three-stage Type Design Process and Loop

When constructing the design process by combining three types of optimization processes, sequential execution is a simple method. The design process at this time is shown in Fig. 2. Decision variables for the total process are electrical circuit parameters, geometrical properties of parts, and the alignment of parts. We will obtain solutions to these using the optimization process in the order of 1, 2, and 3. The problem at each stage is not completely independent, and a part of the information obtained in the previous stage is utilized for the next. As output, the loss of electrical circuits is obtained at stage 1, the size of parts from stage 2, and the total size from stage 3. The degree of miniaturization and higher efficiency is evaluated by integrating these.

This process has loops in two places (red in Fig. 1). The loop of loop 1 is to be reduced in this paper. When the difficulty of the feasibility of parts manufacturing satisfying the target characteristic became clear from the result of stage 2, this returns to stage 1. The optimization problem is redefined at stage 1 to obtain a solution, and stage 2 is executed again. In order to prevent this loop, it is necessary to set the characteristic value prospected to be realized at stage 1 in the design space. If it is within the range where past knowledge can be utilized, predictions can be performed. It is difficult for new parts and custom parts.

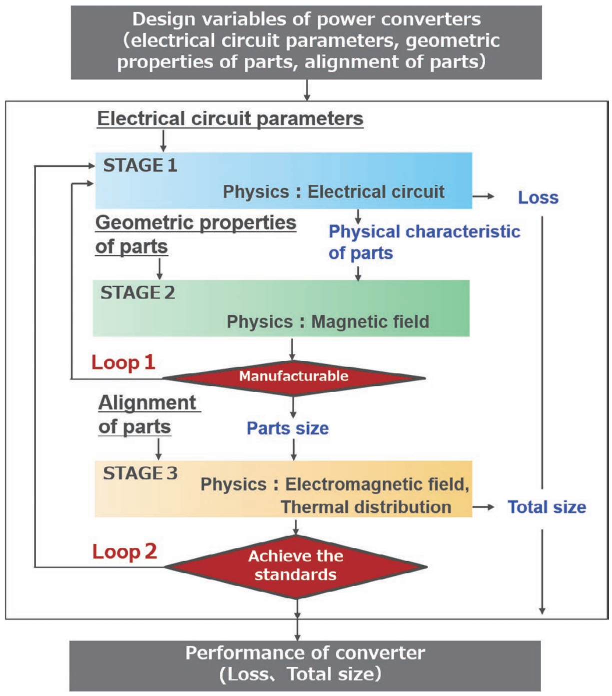


Fig. 2 Three-stage Type Design Process to Be Executed Sequentially

2.3 Two-stage Type Design Process without Loop 1

The two-stage type optimization process in which the loop due to loop 1 was reduced is shown in Fig. 3. The largest difference from the three-stage type is the point that the content at stage 2 is included in stage 1. Specifically, two types of electrical circuit parameters and geometrical properties of parts are set in the decision variables of stage 1. Electrical circuit parameters greatly relying on the shape of parts are excluded from the design space, and are alternatively set as geometrical properties of parts. In addition, characteristics (electrical circuit parameters) are obtained from the geometrical properties of parts by magnetic field analysis prior to performing electrical circuit analysis. The optimization process for electrical circuit parameters is implemented using these. The detailed flow will be described in Subsection 3.3. In this case, electrical circuit characteristics and electrical circuit parameters, as well as geometrical properties of parts for realizing it, are simultaneously obtained by the result of stage 1. This is assumed to be the optimization process for electrical circuit parameters considering the geometrical properties of parts, and called stage 1′. Since the following flow is similar to the three-stage type, discussions will be performed by limiting to the above point.

On the other hand, simulation of magnetic field analysis, in addition to electrical circuit analysis, is run in stage 1′. Therefore, calculation time during the optimization process cannot help increasing. For this, calculation time is shortened by substituting the neural network (NN)[11] of machine learning.

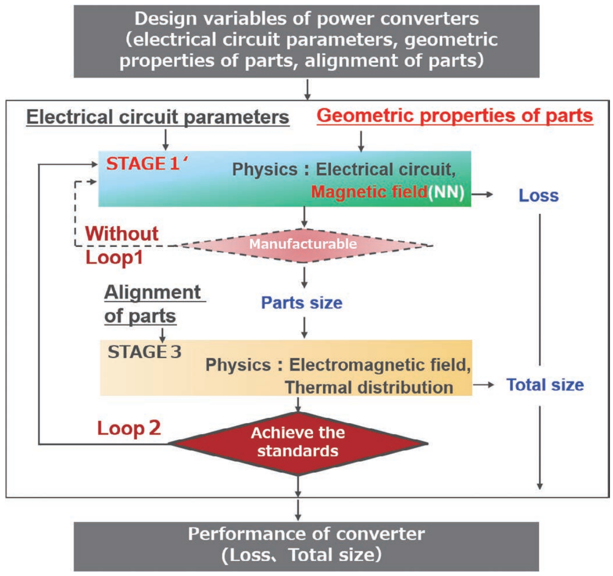


Fig. 3 Two-stage Type Design Process without Loop 1

2.4 NN of Alternative of Simulation

In order to shorten the calculation time of the optimization process, NN is substituted for the simulation. A regression model is created by defining the geometrical properties of parts in the input layer of NN and defining the characteristics in the output layer. The dataset for training data is prepared by simulation. This technique has a preceding example, and the efficient sampling method for reducing the data collection costs has been studied in recent years[12].

The process using NN has two points of advantage. The first point is that the width of the range of design is expanded. In the stage of the conceptual design of power electronics converters, it is difficult to narrow down to one electrical circuit topology, and multiple candidates sometimes remain. However, the specification of applicable parts is often common in spite of the topology. Therefore, time per once spent for solving optimization problem is shortened by using NN in the prediction of the characteristics of common parts. This means the optimization process of one type of electrical circuit topology can be executed in a short time. Thus, the number of electrical circuit topologies that can be studied at the same time can be increased in comparison with the case using a simulation. Since the study of topologies affects the performance of power electronics converters, the possibility of leading to the improvement of performance by widening the range of design is generated.

The second point is that design process can be shortened by utilizing the model that was learned as technical assets in another design. For example, since magnetic parts and heat radiators sometimes use general-purpose products, the extensibility of the learning model is high. In addition, when the simulation takes a lot of time, the model contributes to the improvement of productivity.

3. Demonstration of Proposal Process through Design of WPT

3.1 Background of Application Example and Purpose

WPT is one of power electronic converters and receives and supplies power without contact. Widening of the range of the power transmission space becomes an added value of the application from the viewpoint of convenience for users. Therefore, widening of the range is required, in addition to miniaturization and higher efficiency. However, the higher efficiency and the widening of the range are in the relation of a tradeoff. Therefore, design is performed by substituting an optimization problem that maximizes efficiency subjecting to the constraint about the range.

Since the degree of freedom of the design for magnetic parts is high when applying the three-stage type to the above study, it is difficult to set a suitable design space considering manufacturability at stage 1. Thus, the feasibility of the optimization process for electrical circuit parameters considering geometrical properties of parts that is stage 1′ of stage type was verified targeting two types of design variable of electrical circuit parameters and geometrical properties of magnetic parts.

3.2 Defined Optimization Problem

Assuming S_1 as an electrical circuit parameter and S_2 as a set of geometrical properties of magnetic parts, decision variables $\boldsymbol{X}$ and $\boldsymbol{Y}$ are defined by formula (1). In formula (2), $\boldsymbol{X}$ and $\boldsymbol{Y}$ were assumed to be vectors taking design variables as elements. Formula (3) was assumed to be an objective function and single-purpose optimization (larger-the-better characteristic) maximizing $F(\boldsymbol{X}, \boldsymbol{Y})$. Formula (4) is an evaluation function and was constructed with the loss of electrical circuit (energy conversion efficiency) $\eta(\boldsymbol{X}, \boldsymbol{Y})$ and a penalty function $p(\boldsymbol{X}, \boldsymbol{Y})$ mentioned later. The value of each term is calculated from the electrical circuit characteristic obtained from the electrical circuit simulation. Design of lower loss (higher conversion efficiency) and that satisfying the constraints more satisfactorily acquires a higher evaluation value. Formula (5) is a penalty function and is used for quantifying the degree of satisfaction of the constraints. The constraints set three types consisting of ZVS, electric regulation of output, and the amount of electric current applied to the devices, and function $p_i(\boldsymbol{X}, \boldsymbol{Y})$ was set individually. When all constraints are satisfied, the penalty value is the maximum 1. Penalty value and evaluation value of dissatisfied design are reduced depending on its degree.

Genetic algorithm (GA)[13] is used for the search algorithm for the optimum solution considering that the design space is discrete due to the manufacturing restriction of parts and that the solution space has multimodality.

$$\boldsymbol{X} \in S_1, \boldsymbol{Y} \in S_2 \tag{1}$$

$$\boldsymbol{X} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \boldsymbol{Y} = \begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} \tag{2}$$

$$Max\ F(\boldsymbol{X}, \boldsymbol{Y}) \tag{3}$$

$$F(\boldsymbol{X}, \boldsymbol{Y}) = \eta(\boldsymbol{X}, \boldsymbol{Y}) * p(\boldsymbol{X}, \boldsymbol{Y}) \tag{4}$$

$$p(\boldsymbol{X}, \boldsymbol{Y}) = \prod_{i=1}^{3} p_i(\boldsymbol{X}, \boldsymbol{Y}) \tag{5}$$

$$\begin{cases} 0 < F(\boldsymbol{X}, \boldsymbol{Y}) < 1 \\ 0 < \eta(\boldsymbol{X}, \boldsymbol{Y}) < 1 \\ 0 < p_i(\boldsymbol{X}, \boldsymbol{Y}) < 1 \end{cases} \tag{6}$$

3.3 Flowchart of Optimization Process for Electrical Circuit Parameter Considering Geometrical Properties of Parts

Detailed flow of stage 1′ is shown in Fig. 4. Decision variables of both X and Y are finally set in the design as electrical circuit parameters. However, they pass through different flows as shown in Fig. 4. X and Y are divided by the degree of feasibility of parts manufacturing, and if it is uncertain, Y of the geometrical properties of parts is used for the decision variable. After the value of Y (yellow) is updated as a dimension, Y is converted from a dimension to a characteristic by magnetic analysis. At this time, NN substitutes magnetic analysis for the simulation in order to raise efficiency. This converted value is adopted as the electrical circuit parameter of the design. The direct value of X (blue) is updated and is set in the design as it is. The electrical circuit characteristic and evaluation value are obtained from electrical circuit analysis using these. Then, decision variable is repetitively updated based on the optimization algorithm. This flow was configured utilizing the business software shown in Table 2 in this example.

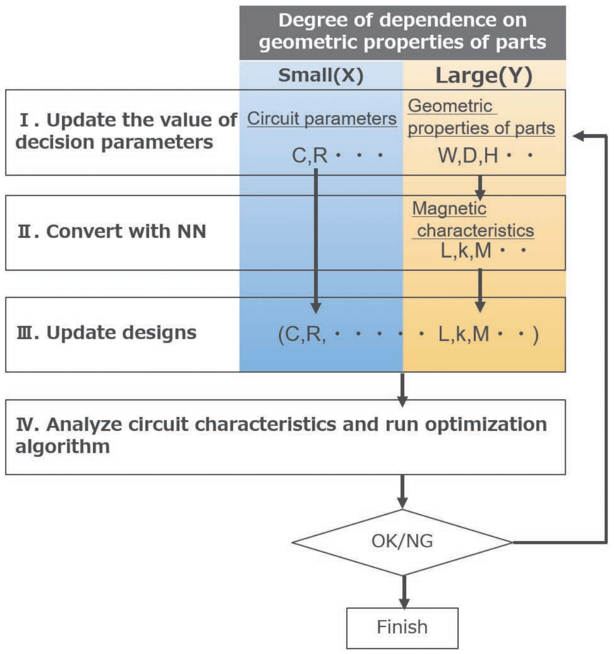


Fig. 4 Flowchart of Optimization Process for Electrical Circuit Parameter Considering Geometrical Properties of Parts

Table 2 Commercial Software Applied

Name of software	Developer	Application
modeFrontier	ESTECO	· Construction of workflow · Execution of optimization algorithm · Creation of NN
Mathcad	PTC	Calculation of electrical circuit characteristic
JMAG	JSOL	Creation of training data for magnetic characteristic

3.4 Execution Result of Optimization

The search process for the solution is shown in Fig. 5. It shows the histogram of the evaluation value F ($\boldsymbol{X}$, $\boldsymbol{Y}$) for each of the 1000 designs in the initial stage (a), middle stage (b), and later stage (c) of the search. In the initial stage (a), the distribution deviates to the class with the lowest evaluation value. The search progresses, the design with high evaluation value is gradually discovered at stage (b), and it changes to a gently-sloping distribution. In addition, it is found that the distribution concentrates to the class with the highest evaluation value and converges. These changes proved that the search for a solution was correctly executed by GA.

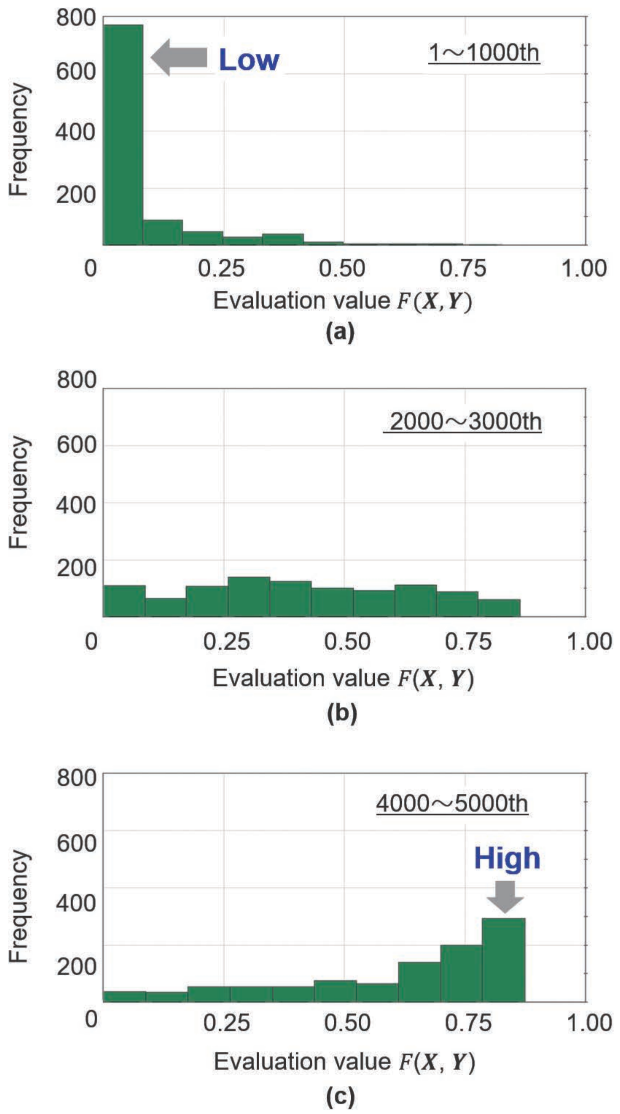


Fig. 5 Histogram of Evaluation Value at Initial Stage (a), Middle Stage (b) and Later Stage (c) of Search

3.5 Demonstration Results and Effects of Two-stage Type Design Process

Stage 1′ of the process in which WPT was proposed as an example was applied to verify feasibility. In order to ensure the manufacturability of parts, the optimization problem was defined using two types of decision variables for the electrical circuit parameter and the geometrical properties of parts. The system was constructed by studying the flowchart for solving this and applying commercial software. In addition, the solution satisfying low loss and the constraints could be derived as a result of the search. The geometrical properties of parts that show the characteristics of the electrical circuit and its characteristics simultaneously became clear from the obtained solution, and the feasibility of a highly efficient process having reduced the loop could be verified. Furthermore, a prototype was manufactured on the basis of this solution, and the realization of an equivalent performance was recognized in the actual measurement (Fig. 6).

Now we describe two points of effect due to this process. The first point is the extension of the width of the design by the application of NN. A comparison of the number of examinable electrical circuit topologies when simulation and NN were used for the derivation of characteristics of magnetic parts in stage 1′ is shown in Table 3. The prediction from NN shortened the execution time per electrical circuit topology by about 70%. Furthermore, since magnetic parts are according to the common specification, the model could be also deployed in multiple electrical circuit topologies. Six different types could be efficiently studied utilizing this. The search range became 1.5 times in the same period in comparison with the case having used a simulation.

The second point is that this process could indirectly contribute to the improvement of performance. Loss of electrical circuits could be reduced by 65% in comparison with the case of having studied without using an optimization process. The reason is that the solution capable of showing higher efficiency while satisfying the constraints about the range could be discovered. The fact that the proposed optimization process could efficiently increase the number of trials while considering manufacturability contributes to the background there.

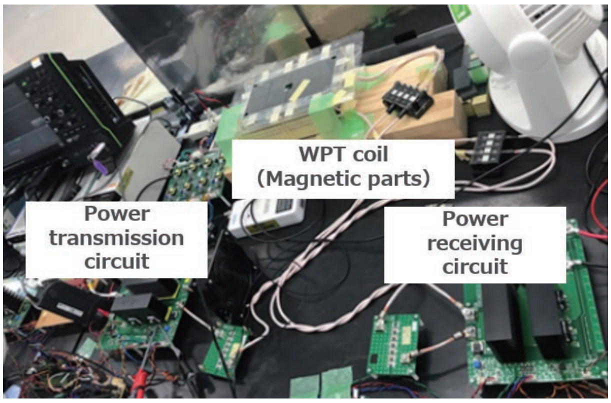


Fig. 6 The Prototype of WPT

Table 3 Calculation Time Shortening by NN and Increase of Number of Study Times

Comparison item	Technique for analyzing magnetic characteristic	
	Simulation	NN
Study period (same)	26 days	26 days
Time for creating training data	—	14 days
Calculation time for executing optimization process per electrical circuit topology	6.6 days (−70%)	2 days
Number of electrical circuit topologies that can be studied	4 (×1.5)	6

4. Conclusions

This paper aimed at the higher efficiency of the design process of power electronic converters using optimization technology and proposed a two-stage type process in which electrical circuit parameters and geometrical properties of parts are studied simultaneously. In addition, the time for simulation spent in the process was shortened by applying the neural network of machine learning. Part of this two-stage type process was applied to wireless power transfer system, and its feasibility was validated. Hereinafter we construct the design process, including parts alignment, to achieve the improvement of productivity.

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