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Optimal Design of Shared Transformer/Reactor for Improving Power Density

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Abstract *— A method that can improve the system's performance is suggested by conducting a structural study of an important passive element inside these pcs. Transformers and reactors are used inside the PCS. This is a study of combining two devices. The advantages of the combination are reducing the weight and volume of the device and increasing the power density. Therefore, the core size optimization was studied to increase the power density of the shared transformer/reactor. The power density can be increased by reducing the core size as the overall device size is minimized, price competitiveness increases. Design variables and constraint conditions were set for optimal design. Optimization was carried out by extracting variable points with the minimum number of points through the DOE method. This was verified through 3D-FEA. It was possible to extract more detailed optimal points and to increase the output density.*

Keywords — *Design of experiment, Optimal design, Power density, Shared transformer/reactor, Thermal analysis*

I. INTRODUCTION

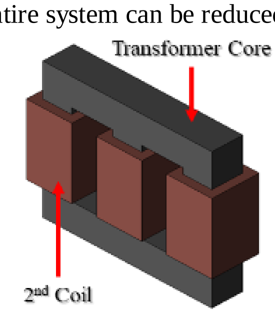
The international community is seriously considering the issue of climate change. Policies are being considered worldwide for carbon reductions, such as net-zero. Renewable energy plays a huge role in reducing carbon emissions. Distributed power system facilities are increasing for renewable energy. Various studies of energy storage systems (ESS) in the system are being conducted[1]. A power conditioning system (PCS) is used for system protection and the control of ESS. Research on passive devices used in PCS is also important[2].

Common types of passive elements (transformers, reactors) can be combined. The combined model is a shared transformer/reactor[3,4]. Optimal design can increase utilization by reducing the volume and weight[5-8]. On the other hand, domestic/international research is still insufficient.

The physical structure and electromagnetic characteristics are different from conventional transformers and reactors. Therefore, it is necessary to analyze the various characteristics of the shared model. Basic models of passive elements (transformers, reactors) used in PCS were studied through simulation. The aim was to develop a power density optimization model of a shared transformer/reactor for power converters considering the output, efficiency, and thermal saturation through design factor analysis. The purpose of developing an optimization model is to improve the power density of the shared transformer reactor.

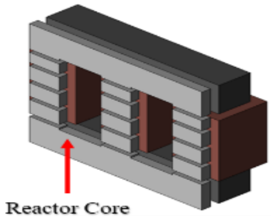
II. MATERIALS AND METHODS

Transformers and reactors are essential for power conditioning systems (PCS) and occupy most weight and volume. A shared transformer/reactor can be made by combining transformers and reactors with similar structures and operating principles. The shared model can improve the power density by reducing the volume and weight. Figure 1 shows the design method of the shared transformer/reactor. The secondary coil for the transformer is wound on the transformer core first. The reactor core is then placed next to it. The core is designed by winding the primary side coil used for both transformer/reactor core. This is a special feature in that the primary winding of the transformer is wound, including the reactor core. Coil usage can be reduced because it shares the roles of transformer and reactor coil. The combination also allows the use of only one steel support in the transformer and reactor. The existing method requires two independent spaces inside the PCS. On the other hand, the feature is that only one place is used, and the volume of the entire system can be reduced.



(a)

This research was financially supported by the Ministry of Trade, Industry, and Energy(MOTIE) and the Korea Institute for Advancement of Technology(KIAT) through the National Innovation Cluster R&D program(P0015360_Development and demonstration of Multi-circuit Power Conversion Device for protection coordination of DC distribution network).



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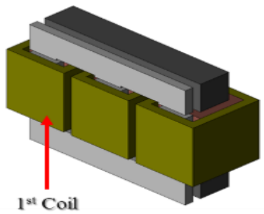
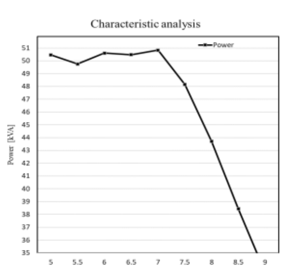


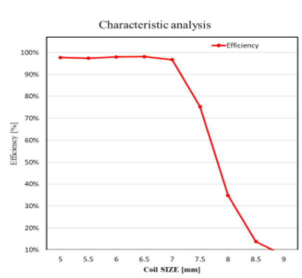
(c)

Fig 1. The combination method of shared transformer/reactor

Normal operation was confirmed by analyzing the characteristics, such as power characteristics and saturation magnetic flux density. The input voltage of the integrated model was 380[V], and the output voltage was 376[V]. The input current was 45[A], and the output current was 44.5[A]. The 50[kVA] reference efficiency was 96[%]. The saturation magnetic flux density was confirmed. The transformer core part was 1.52[T], and the reactor core part was 0.82[T]. The core material 23PH090 did not exceed the saturation magnetic flux density of 2.2[T].

The coil is an important design parameter in transformers and reactors. The output characteristics of a device may vary depending on the material. As the number of turns varies with the coil thickness, it also affects the efficiency and output capacity. Therefore, the finite element analysis was performed on the output characteristics by increasing the coil thickness from 5[mm] to 9[mm] in 0.5[mm] intervals. The space factor was calculated as an average of 35[%], considering it is a circular coil. The calculated number of turns was changed from 127 turns to 412 turns, considering the window between each transformer phase. Figure 2.





(a) **(b)**

Fig 2. Characteristic analysis result according to coil thickness (a)Power(b)Efficiency

Shows the characterization results. Among them, it was designed with the highest efficiency of 98.18[%] while satisfying the output capacity of 50[kVA] at 244 turns-141 turns with a coil thickness of 6.5[mm]. The weight of the designed shared model was compared with general transformers and reactors. The weight of the steel supports used as coils and supports was reduced to 217[kg]. The power density for 50[kVA] output capacity was 0.46[kVA/kg]. This model is the reference model for optimization design.

III. Optimal design of shared transformer/reactor

A. Shared transformer/reactor optimal design

The shared transformer/reactor to be optimized is not a typical type of device. 3D modeling is required for electromagnetic field analysis, which takes a relatively long time. The goal of optimization is to maximize the power density. If the output density of the passive element (Shared Transformer/Reactor) is increased, it can be manufactured in a smaller size. When passive elements such as PCS are mounted, space utilization is further increased, and the degree of design freedom increases. Therefore, an optimization study was conducted to improve the output density. The device can be made small by minimizing the core's path, width, height, and thickness. However, the characteristic output changes in many ways according to various design variables. Hundreds to thousands of models are produced depending on the combination of variables. It isn't easy to perform finite element analysis simulations by 3D modeling each combination. Therefore, it is important to predict the optimal value of each variable by analyzing the minimum number of models using the optimization technique and program. The method of sampling points is called Design of Experiment (DOE)[9-10]. Plan and conduct experiments and analysis methods to obtain optimal information and values at a given cost, time, and efficiency. Next, it determines the factor conditions be optimized, and the accuracy of prediction is improved. Depending on the number and range of variables, there should be no overlap. The goal is to achieve the best effect with the minimum number of items. Optimal design variable points can be extracted. Optimization was conducted using the DOE method and CMA-ES method[11]. The conditions were set, and the optimal design was carried out according to the flowchart in Figure 3.

To extract optimal sample points, objective functions, constraint functions, and design functions must be selected first. The constraint function was selected as a capacity of 50[kVA] and an efficiency of 97[%], referring to the reference transformer. Table 1 lists the optimal design variables.

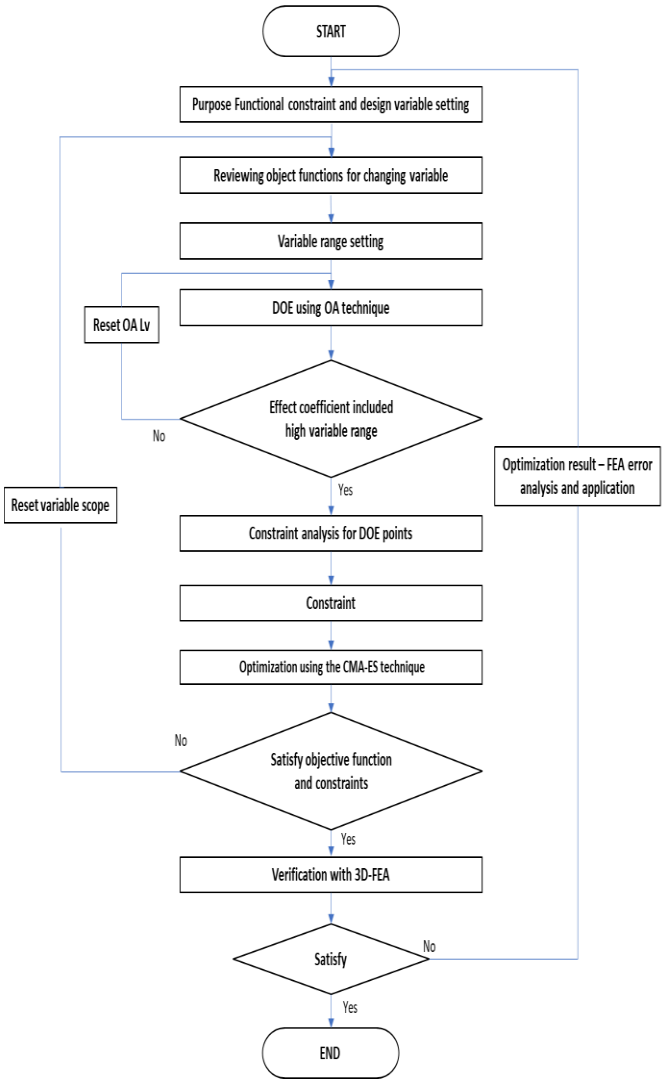


Fig 3. Power density optimization flowchart

Table 1 Optimization Variables

	Item			Condition	Initial model
Objective function	Shared Transformer /Reactor Power Density		[kVA/kg]	MAX	0.45
Constraint function	Output capacity		[kVA]	≥50	50.68
	Power efficiency		[%]	≥97	97.31
variable	X1	Core(W)	[mm]	410≤ X1 ≤460	460
	X2	Core(H)		350≤ X2 ≤400	400
	X3	Core(Path)		70≤ X3 ≤80	80
	X4	Core(T)		70≤ X4 ≤80	80
	X5	Reactor		20≤ X1 ≤30	20

Table 2Sample points using DOE and FEA result

Sample points extracted through DOE						Results for samples through FEA		
ID	**X1**	**X2**	**X3**	**X4**	**X5**	**Efficiency [%]**	**Weight [kg]**	**Power [kW]**
1	410	350	70	75	20	70.83	163	46.59
2	410	350	70	80	30	88.45	178	48.47
3	410	350	75	80	25	96.55	174	50.43
4	410	350	80	80	20	98.33	169	51.32
5	410	375	70	70	25	53.63	178	43.33
6	410	375	75	75	25	88.67	185	48.58
7	410	375	80	70	25	88.74	180	48.23
8	410	375	80	80	20	98.05	188	51.03
9	410	400	70	70	30	53.28	199	42.5
10	410	400	75	70	20	69.22	195	46.06
11	410	400	75	75	30	88.33	208	48.27
12	410	400	80	75	30	96.32	209	50.27
13	435	350	70	75	25	72.89	170	46.35
14	435	350	75	70	20	72.54	163	46.64
15	435	350	75	75	30	89.28	179	48.55
16	435	350	80	80	30	97.81	183	50.79
17	435	375	70	70	20	52.06	176	43.86
18	435	375	70	80	30	87.6	198	48.39
19	435	375	75	80	20	96.45	190	50.58
20	435	375	80	75	25	96.56	189	50.43
21	435	400	70	70	30	53.23	202	42.51
22	435	400	75	70	25	70.67	199	45.93
23	435	400	80	75	20	96.4	202	50.46
24	435	400	80	80	25	97.92	214	50.97
25	460	350	70	75	25	72.03	173	46.31
26	460	350	75	70	20	72.96	163	46.41
27	460	350	80	70	25	89.41	168	48.19
28	460	350	80	70	30	89.68	174	47.92
29	460	375	70	75	20	69.96	185	46.51
30	460	375	75	75	30	88.79	196	48.37
31	460	375	75	80	30	96.56	203	50.31
32	460	375	80	70	30	88.82	191	48.02
33	460	400	70	80	20	85.88	208	48.75
34	460	400	70	80	25	86.36	214	48.53
35	460	400	75	80	25	96.28	216	50.47
36	460	400	80	75	20	96.36	204	50.49

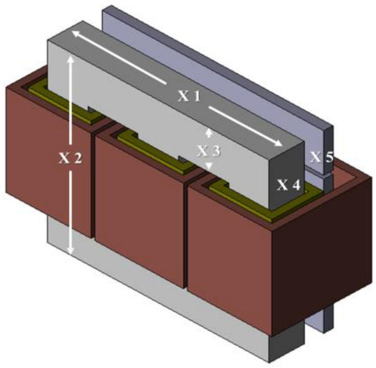
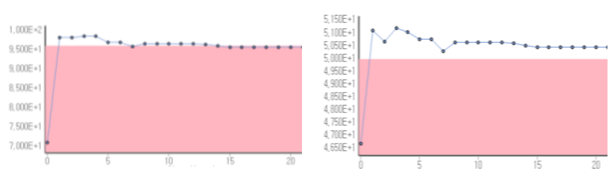


Fig 4. Design variables in the model

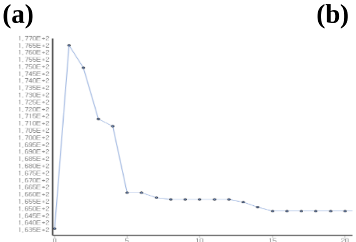
B. Characteristic analysis of the optimally designed shared transformer/reactor

The goal of the optimal design is to improve the power density so that thermal saturation and magnetic flux saturation do not occur. In general, combinations are performed in three levels (lowest, middle, and maximum). At this time, the combination was carried out with five variables, from X1 to X5. A sample point is obtained for 36 points, as shown in Table 2. The values were extracted through finite element analysis for samples extracted using DOE.

The following extracts more accurate and detailed design points. A meta-model can be extracted, and CMA-ES can be used to obtain the optimal design variable points. The constraints on the optimal point were analyzed to check that all the conditions were satisfied. As shown in Figure 5, the constraints (a) and (b) converged, and the convergence of the objective function was confirmed (c).



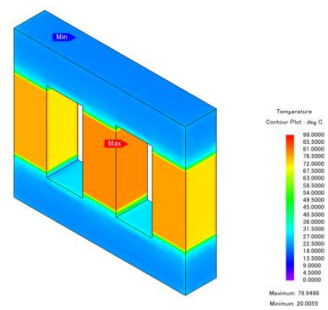
(a) **(b)**



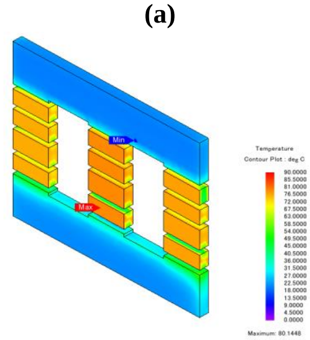
(c)

Fig 5. Constraint function and objective function convergence result (a) Efficiency constraint (b)Power constraint (c)Objective function

The constraints on the optimal design variable points were checked to determine if all conditions were satisfied. The optimal model was verified through 3D-FEA. The optimal design variable points through CMA-ES from X1 to X5 in Fig. 4 were applied to the 3D model and designed. The 3D-FEA analysis result was compared with the Optimal (CMA-ES) prediction model. A reliable, optimal model was designed. 3D-FEA analysis confirmed that stable operation is possible. The saturation magnetic flux density of 1.45[T] can be confirmed at the output capacity of 50[kVA] or more and an efficiency of 97[%] or more. Thermal characteristic analysis of the integrated model has a temperature of 78.94[℃] at the transformer side and 80.14[℃] at the reactor. A more optimal state can be confirmed compared to the reference model. The weight was reduced by about 40[kg] while maintaining the output characteristics, as shown in Table 3. The output density was maximized from 0.46[kVA/kg] to 0.61[kVA/kg] to meet the research goal.



(a)



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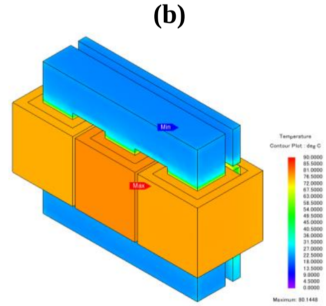

(c)

Fig 6. Thermal characteristic analysis results(a) Transformer core (b)Reactor core (c)shared transformer/reactor

Table 3 Optimal design variables and results

		Unit	Initial	Optimal model (by CMA-ES Optimal)	Optimal model (verified result by FEA)
Design Variable	X1	[mm]	460	412.5	
	X2	[mm]	400	350	
	X3	[mm]	80	79.5	
	X4	[mm]	80	74.8	
	X5	[mm]	20	20	
Power		[kVA]	50.68	50.074	50.54
Efficiency		[%]	97.31	98	97.64
Weight		[kg]	217	169	164
Power Density		[kVA/kg]	0.46	0.60	0.61

IV. CONCLUSIONS

In this study, characteristic analysis was conducted by changing the thickness of the coil of a shared transformer/reactor, which is a combination of passive elements used in PCS of the ESS. The coil was designed with the highest efficiency from 6.5[mm] to 98.18[%] by analyzing the characteristics from 5[mm] to 9[mm] in 0.5[mm] increments. Normal operation was confirmed by analyzing the input/output voltage, current, saturation magnetic flux density, and thermal characteristics in a shared model with an output density of 0.45[kVA/kg], combining a transformer and a reactor. It was possible to confirm the result suitable for the output capacity of 50[kVA]. This model was used as a reference to optimize the power density. Optimization was performed for five design variables through the design of the experimental method. If the output density is improved, the usability of space increases, the degree of freedom in design increases, and it has the advantage of being able to manufacture in a small size. The total weight was reduced by 25[%] compared to the initial model. It was possible to increase 0.16[kVA/kg] through the optimal design to meet the research goal of maximizing the power density.

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