Application of Artificial Intelligence in Optimization of Solid-State Transformer Core for Modern Electric Vehicles Using Multi-Objective Genetic Algorithm

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I. Introduction

- Solid State Transformers are increasingly becoming a favored alternative to traditional low frequency transformers due to their small size and excellent efficiency, particularly in the field of Electric Vehicles (EV), which has seen rapid growth in recent years.
- This research offers a multi-objective AI-based high-frequency transformer (HFT) design optimization for a 10kW, 750kHz solid state transformer (SST).
- The HFT is designed using a multi-objective genetic algorithm optimization technique that reduces core volume (maximizing power density), total transformer losses, and overall cost from the set of multiple Pareto-optimal solutions (POS).

II. Problem Formulation

- Climate change is one of the most pressing concerns confronting the globe today, and it is mostly caused by ever-increasing greenhouse gas (GHG) emissions
- Resulting in massive growth in the net-zero carbon automobile industry since the fossil-fuel transportation industry is responsible for a significant share of the GHG emissions.
- However, this growth has been hindered with the efficiency of the energy storage and management system of the EV power train

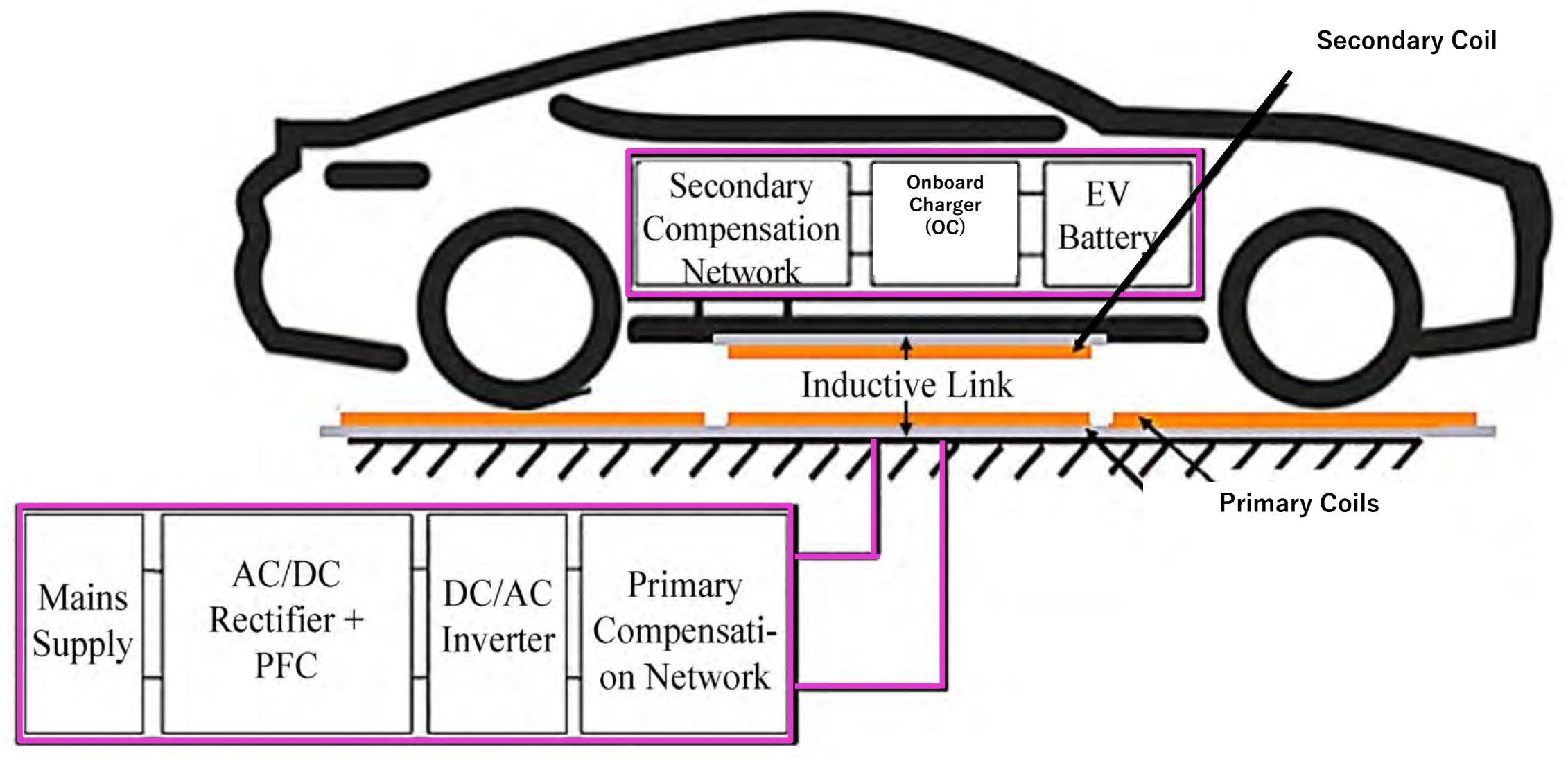

Fig. 1. Schematic of an EV using WPT with On-board Charger

- If the energy storage system could be optimized, the range and overall performance of the EV would be largely improved
- The storage limitation has led to the increased research focus in Wireless Power Transfer (WPT)
- Which has necessitated the use of an AC to DC converter known as the On-board Charger (OC)
- The major component in the OC is the HFT which accounts for more than 60% of OC volume

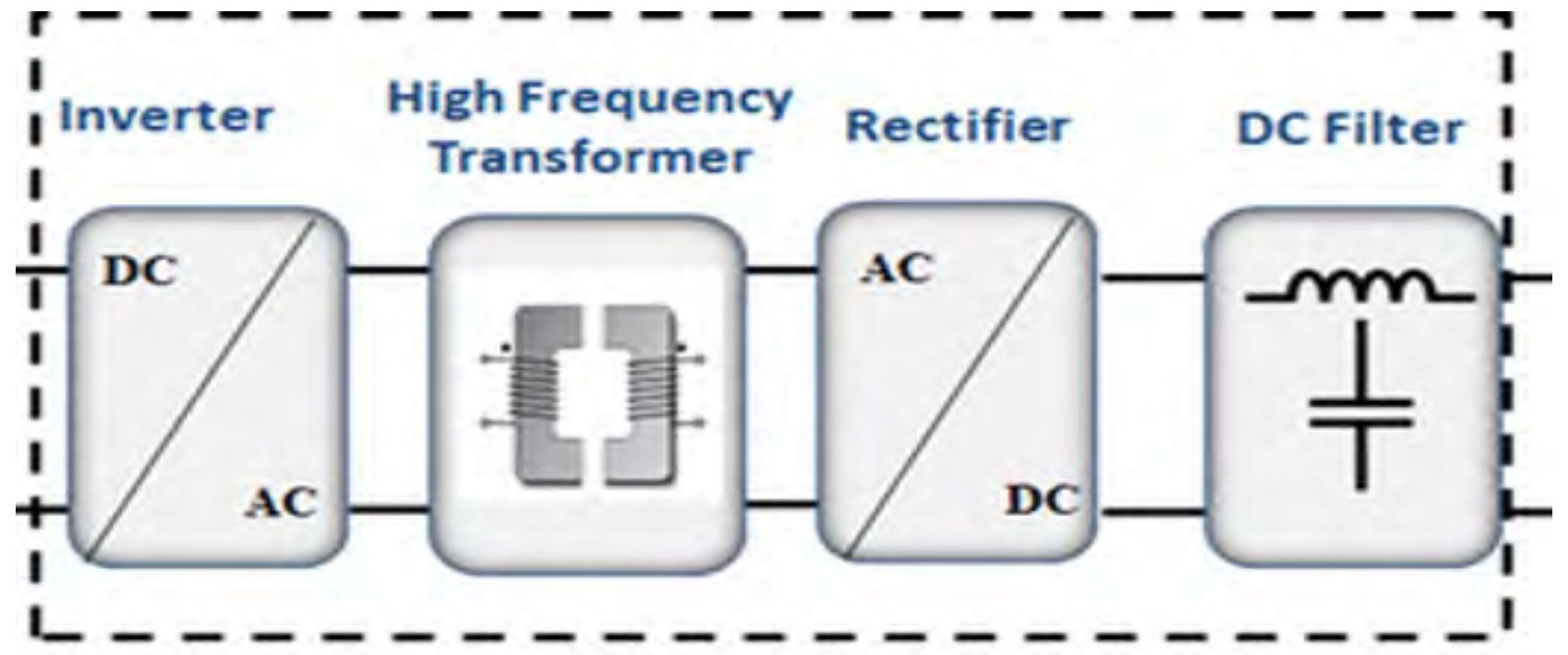

Fig. 2. High Frequency Transformers in On-board Charger for Voltage Step-up

III. HFT Analytical Approach

- To optimize the HFT, this work presents the use of physics and AI-based multi-objective genetic algorithm optimization technique to optimize the core
- Three high permeability soft magnetic core materials namely Ferrite(3C94), Amorphous(Metglas 2605SA1) & Nanocrystalline(Vitroperm 500F) were investigated
- The flux density optimization criteria was used in conjunction with the transformer design technique

$$B_{opt} = \frac{(h_c k_a \Delta T)^{2/3}}{2^{2/3}\left[\rho_c k_w k_u\right]^{1/12}\left[k_c K f^{\alpha}\right]^{7/12}}\left[\frac{K_v f k_f k_u}{\sum VA}\right]^{1/6}$$

- The equation above was used to compute the HFT's optimal flux density
- The core dimension was determined using the core area product illustrated below

$$A_p = \left[\frac{\sqrt{2}\sum VA}{K_v f B_{opt} k_f K_t \sqrt{k_u \Delta T}}\right]^{8/7}$$

- The core power loss was determined using the improved generalized Steinmetz Equation (iGSE)

$$P_{loss}^{core}|_{iGSE} = \frac{1}{T}\int_0^T k_i\left|\frac{dB(t)}{dt}\right|^{\alpha}(\Delta B)^{\vartheta-\alpha}dt$$

Table. 1. Steinmetz Constant for core materials used in optimization

Parameter	Ferrite 3C94	Amorphous	Nanocrystalline
$K(W/m^3)$	17.10	1.36	2.30
α	1.46	1.51	1.32
ϑ	2.75	1.74	2.12

IV. Multi-objective Optimization

Objectives Process Flow

This study uses the multi-objective genetic algorithm technique to optimize three important parameters of the HFT's design namely:

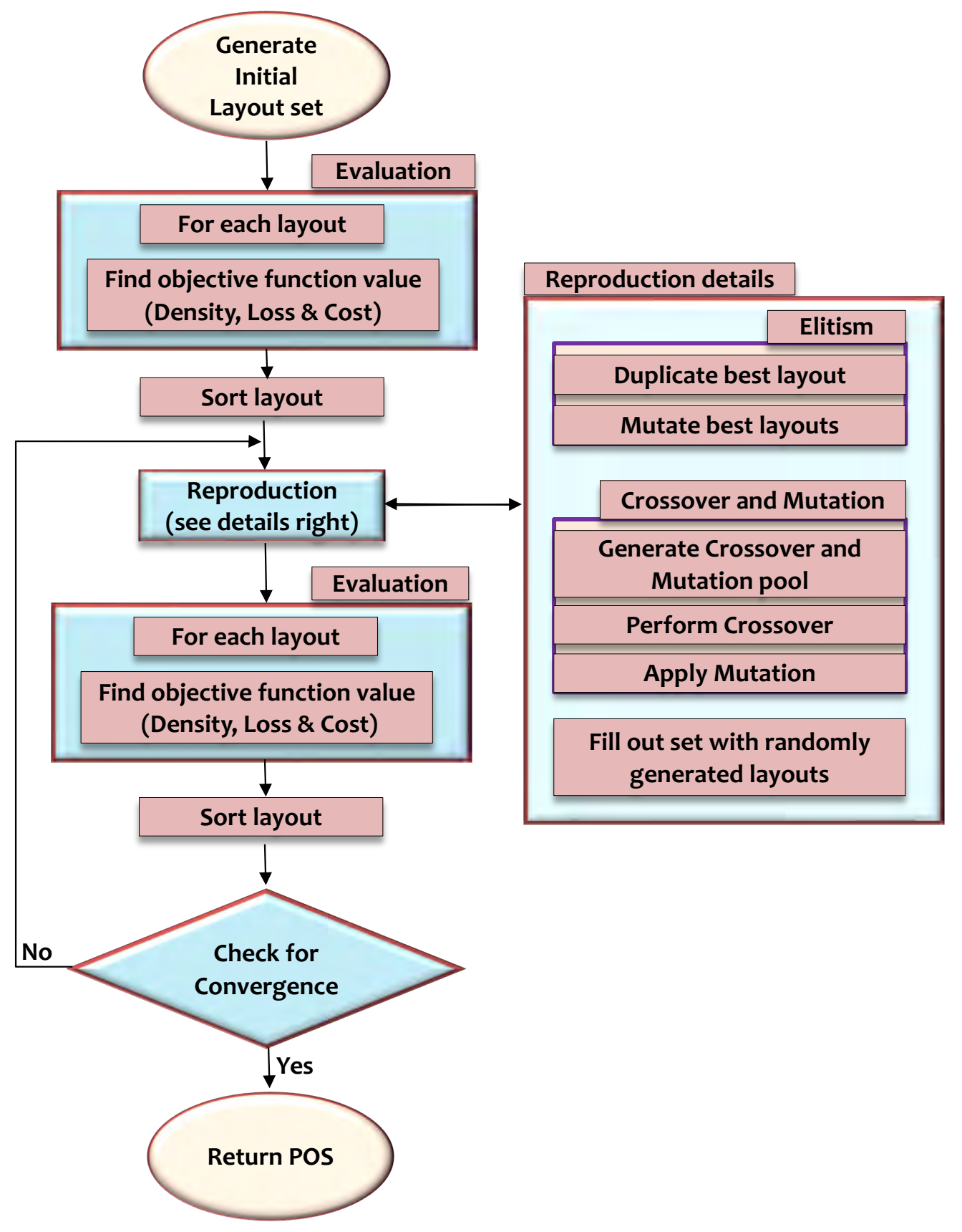

Fig. 3. Genetic Algorithm Optimization Flowchart

1. The Total Power Loss: Eddy current and hysteresis losses increase drastically at high frequencies
2. The Power Density: The volume of transformers can be greatly reduced at higher frequencies
3. Total Cost: The HFT's cost is also a key consideration for optimization, the price of Litz wire and the different core materials

V. Design Optimization Constraints

The constraints employed are based on the efficiency, geometry and Power Electronic Converter of the SST

- Efficiency Constraint: The HFT efficiency must be higher than the predetermined value, from the manufacturer.

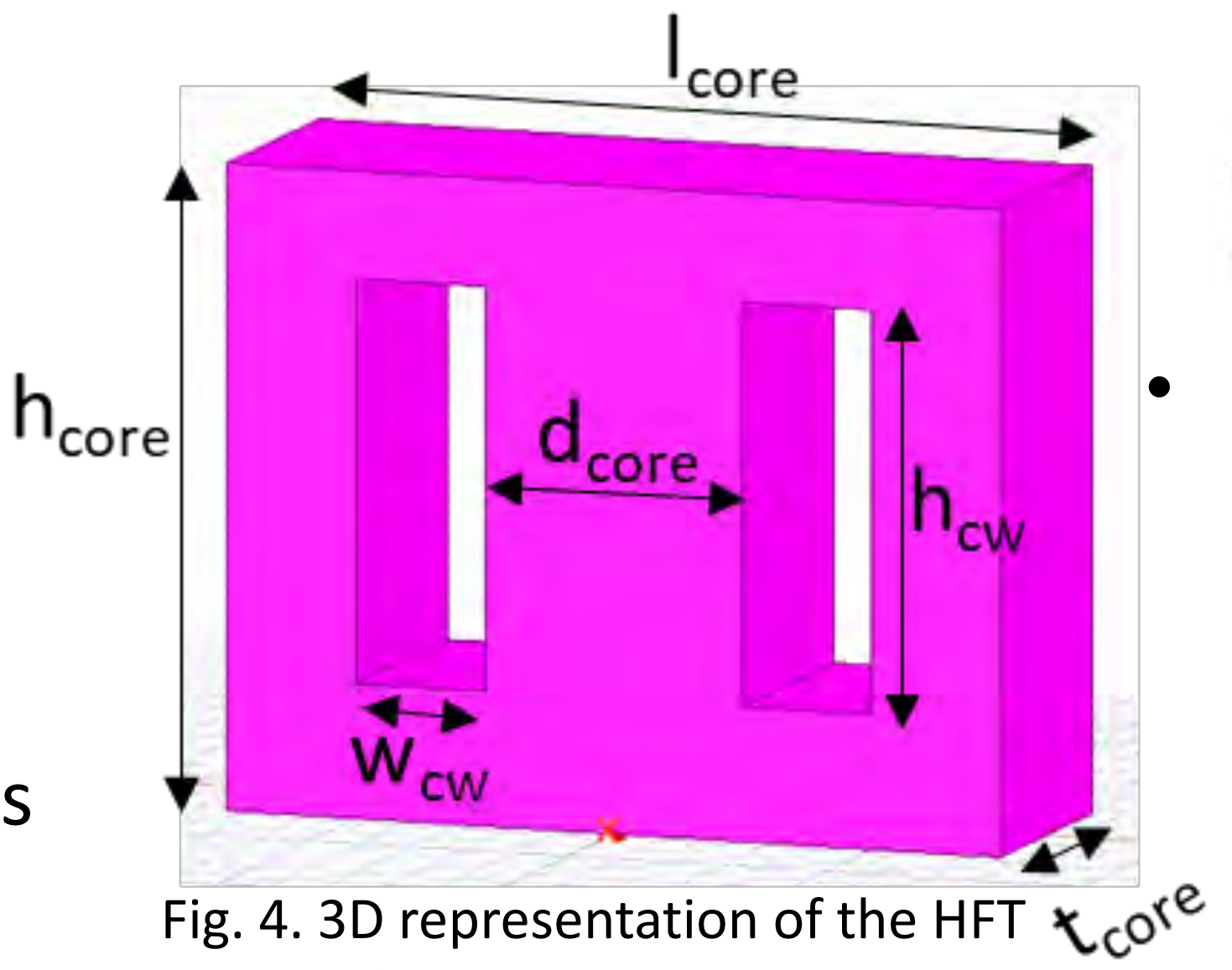

Fig. 4. 3D representation of the HFT core with optimization dimensions

$$\frac{P_{output}}{P_{output} + P_{total}} \geq \eta_m$$

- Core Dimensions Constraints: For the optimized HFT to be implemented in a realistic way, the dimensions of the core must be carefully chosen
- Power Electronic Converter Constraints: For SST applications, DAB LLC resonant converters are widely employed because of its extensive voltage regulation and ability to achieve smooth switching over a large load range.

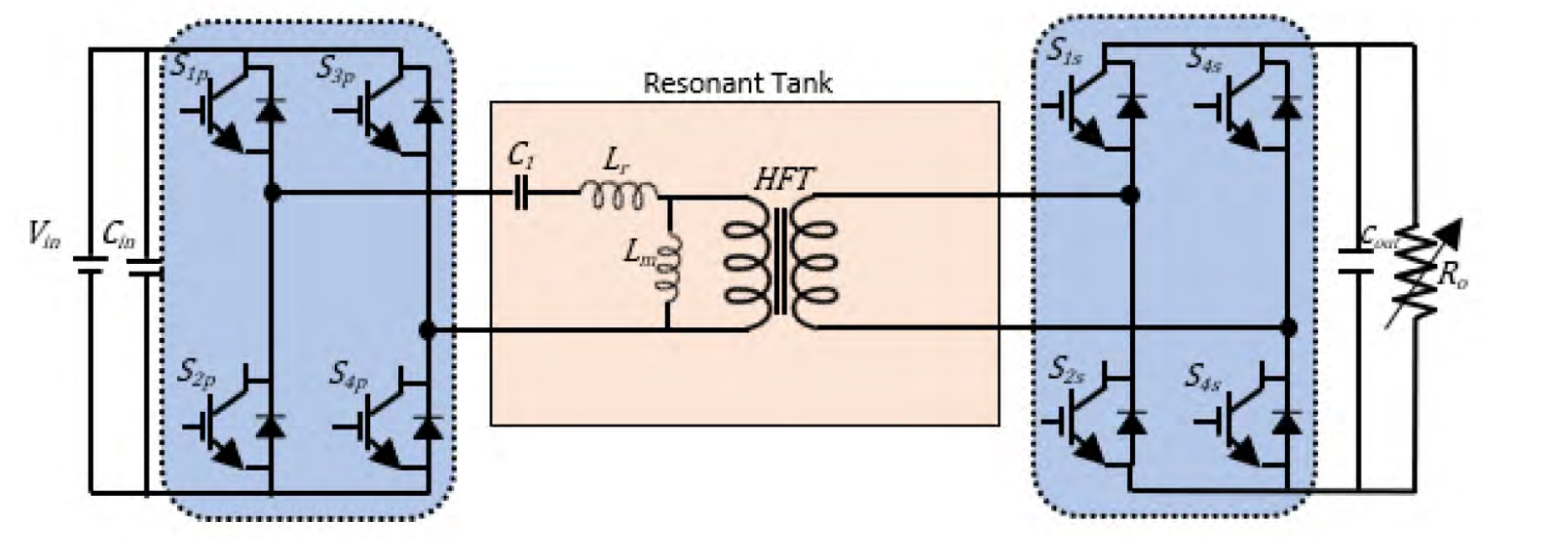

Fig. 5. Schematic of a resonant LLC Dual Active Bridge converter

VI. Result

- ANSYS Maxwell program and MATLAB were used to simulate and optimize the HFT core.
- An elitist non-dominated sorting genetic algorithm (NSGAII) is utilized to find the Pareto-optimal solution

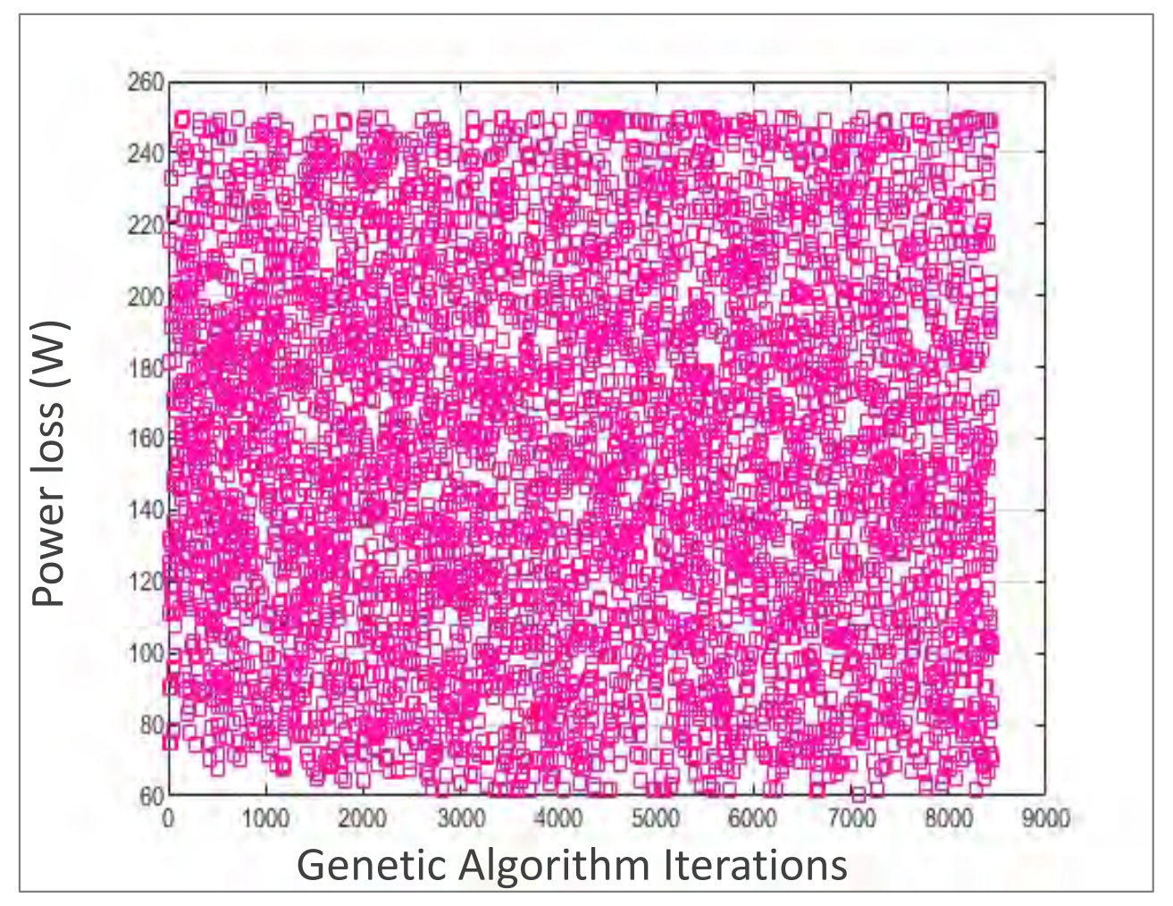

Fig.6. HFT power loss vs the number of iteration during optimization

- multi-objective optimization produced 10 Pareto-optimal solutions for each of the core materials
- The various dimensions of the cores can be chosen depending on the priority objective.
- The switching frequency of the HFT is set at 750kHz

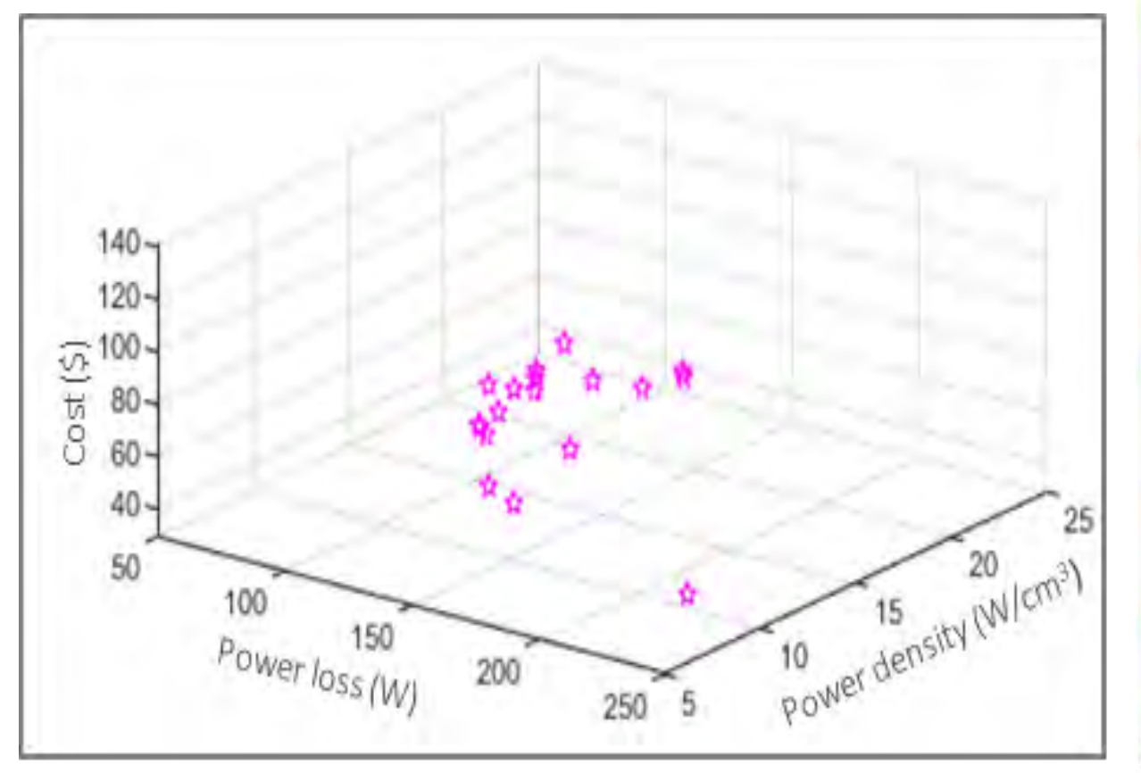

Fig.7 Pareto-optimal solutions for the multi-objective problem

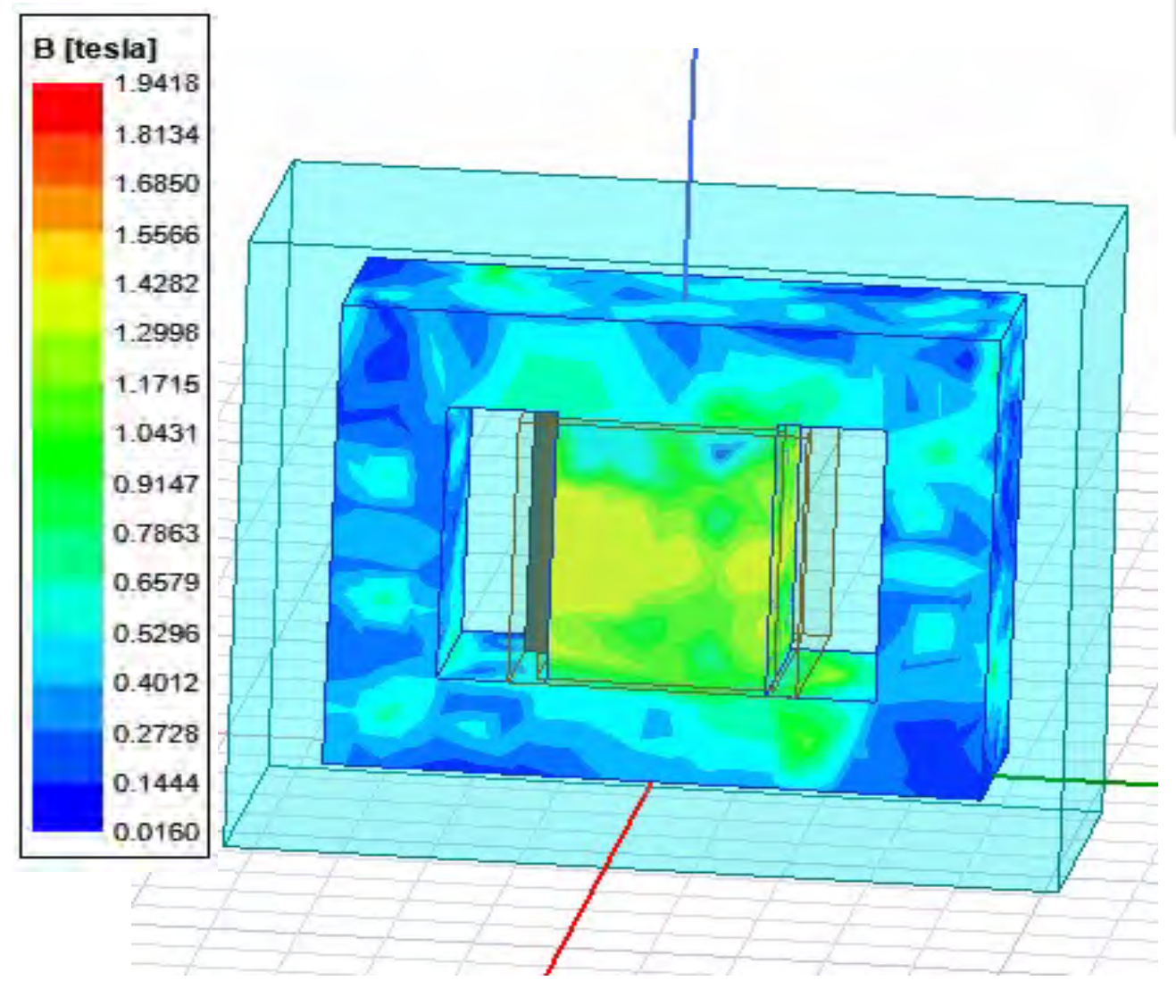

Fig.8 Ansys Maxwell Flux density distribution Simulation of one of the Iterations

VII. Result Cont'd

Table. 2. Pos Results for the 10kW, 750kHz Ferrite, 3c94 HFT Core

	Design Variables				Objective Functions			
	h_{core}	L_{core}	t_{core}	d_{core}	p_{total}	$p_{density}$	c_{cost}	Eff.
1	6.87	7.07	2.96	3.19	1.85	25.12	57.01	99.99
2	5.67	7.05	2.19	3.12	2.39	19.62	45.95	99.98
3	6.60	7.17	2.44	3.27	3.37	15.35	57.73	99.97
4	6.61	7.21	2.38	3.75	4.22	12.97	66.69	99.96
5	6.58	7.09	2.20	3.10	5.34	12.23	55.51	99.95
6	6.88	8.17	2.50	4.24	5.95	9.51	88.34	99.94
7	9.79	8.43	1.86	4.88	46.48	1.88	177.02	99.54
8	9.55	8.21	1.57	6.38	56.27	1.54	204.26	99.44
9	10.63	8.14	1.74	7.46	64.98	1.31	257.63	99.35
10	10.60	8.27	1.66	7.82	71.77	1.20	271.98	99.28

Table. 3. Pos Results for the 10kW, 750kHz Amorphous, METGLAS 2605SA1 HFT Core

	Design Variables				Objective Functions			
	h_{core}	L_{core}	t_{core}	d_{core}	p_{total}	$p_{density}$	c_{cost}	Eff.
1	7.51	8.14	2.71	7.42	244.07	6.24	123.67	99.94
2	8.08	7.93	3.00	7.92	231.72	6.51	136.91	99.93
3	8.00	7.92	3.00	7.71	221.21	6.82	132.10	99.93
4	7.70	8.12	2.79	6.07	209.88	7.24	104.15	99.93
5	7.61	8.09	2.89	5.68	177.73	8.54	96.44	99.91
6	7.45	7.65	2.97	6.67	157.46	9.54	102.54	99.90
7	7.47	8.18	3.00	5.06	143.16	10.54	84.32	99.89
8	6.84	7.22	2.93	3.90	74.51	20.02	51.76	99.80
9	5.15	7.05	1.96	3.09	75.51	20.22	31.49	99.80
10	5.02	7.00	1.96	3.01	67.27	22.61	29.25	99.77

Table. 4. Pos Results for the 10kW, 750kHz Nanocrystalline, Vitroperm 500F HFT Core

	Design Variables				Objective Functions			
	h_{core}	L_{core}	t_{core}	d_{core}	p_{total}	$p_{density}$	c_{cost}	Eff.
1	5.72	7.01	2.39	3.18	32.16	24.51	54.69	99.68
2	5.20	7.01	2.06	3.06	34.76	22.86	47.35	99.65
3	5.01	7.01	1.87	3.00	39.67	20.13	44.29	99.60
4	7.09	7.41	2.82	3.38	45.84	17.07	75.90	99.54
5	6.34	7.63	2.53	3.72	50.11	15.72	76.18	99.50
6	5.53	7.48	2.09	4.45	58.64	13.61	76.89	99.41
7	5.41	7.02	1.88	3.97	59.34	13.55	62.91	99.41
8	5.84	7.68	2.40	7.22	73.97	10.57	135.06	99.26
9	6.95	7.51	2.45	4.40	79.35	10.07	97.42	99.21
10	6.29	7.15	2.02	4.70	89.49	9.07	89.00	99.11

- Ferrite cores have low power density and becomes relatively expensive due to the large volume but have low losses compared to the Metglas.
- The Amorphous cores, Metglas, have relatively high-power density and are less expensive compared to the Ferrites but they have high losses.
- The nanocrystalline, Vitroperm 500F, has high power density, low power loss and low manufacturing cost, resulting in its frequent use in high-frequency power applications.

VIII. Conclusion

The optimization results show that nanocrystalline is the best core material based on the set objective. The core parameters dimension constraints were formulated in a way to ensure the feasibility of practical implementation based on off-the-shelf core dimensions. Power density, efficiency, and cost are the three goal functions in the optimization, and they are all important in HFT design. Within the geometric and power electronic converter limits, various trade-offs must be made to maximize any of these goals. The best design can be chosen among the Pareto-optimal alternatives depending on the priority of each goal. Most of the Pareto-optimal solutions had efficiencies above 97.5%, which is ideal for SST designs.

IX. Acknowledgment

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X. References

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