Comparative Design Study of HTS Synchronous Motor with Inner and Outer Rotor Type Based on Multi-Objective Optimization

Seok-Won Jung, Jonghoon Yoon, Kibum Choi, Jeseok Bang, Uijong Bong, and Seungyong Hahn

Seoul National University, Seoul, Republic of Korea

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Abstract – We report a design comparison between the inner and the outer rotor type for a partial high temperature superconductor (HTS) synchronous motor based on a multi-objective optimization. The partial HTS synchronous motors with the inner and outer rotor type are respectively optimized by a multi-objective optimization which considers three characteristics; specific power (power per weight), power density (power per volume), and HTS tape consumption, simultaneously. At this time, the performance of each design is evaluated through the electromagnetic finite element method. Finally, the results obtained by optimization are compared between the inner and the outer rotor type.

I. Introduction

In many industrial applications, there has been a growing need for electrical motors having performance such as high specific power, low energy consumption, etc. An electrical motor with high temperature superconductor (HTS) coils allows to offer those advantages due to the very high current density compared with conventional superconductor motors. Specially, partial HTS motors can be designed in considering two types of synchronous motor: an inner and an outer rotor type. Since each type has advantages and disadvantages in motor characteristics, a design comparison between each type is necessary. Therefore, in this paper, we report a design comparison between an inner and an outer rotor type for an HTS synchronous motor based on a multi-objective optimization with the electromagnetic finite element method.

II. Multi-Objective Optimization

Introduction to Multi-Objective Optimization (MOO)

- ✓ Involving simultaneous optimization of multiple objectives
- ✓ Applied to many real-world design or decision-making problems
  - Design of electric machines, optimal control, electric power systems, etc.
- ✓ Mathematical term of MOO problems

$$\begin{cases} \text{Minimize or Maximize} \quad \boldsymbol{f}(\boldsymbol{x}) = \{f_1(\boldsymbol{x}), \cdots, f_M(\boldsymbol{x})\}, \\ \text{subject to} \quad \boldsymbol{g}(\boldsymbol{x}) = \{g_1(\boldsymbol{x}), g_2(\boldsymbol{x}), \cdots, g_K(\boldsymbol{x})\} \le 0, \\ \qquad \boldsymbol{h}(\boldsymbol{x}) = \{h_1(\boldsymbol{x}), h_2(\boldsymbol{x}), \cdots, h_L(\boldsymbol{x})\} = 0, \\ \qquad \boldsymbol{x} = \{x_1, x_2, \cdots, x_N\} \in \mathbb{R}^N \end{cases}$$

- $\boldsymbol{f}$: M-dimensional objective function
- $\boldsymbol{g}$: K-dimensional inequality constraint
- $\boldsymbol{h}$: L-dimensional equality constraint
- $\boldsymbol{x}$: N-dimensional variable vector
- $\mathbb{R}$: feasible space

- ✓ Finding nondominated solutions (or pareto- front solutions)
  - ■ Dominant solution [@ MOO Case: minimizing objective functions]

$$\begin{cases} f_j(\boldsymbol{x}) \le f_j(\boldsymbol{y}) \text{ for all } j = 1, 2, \cdots, M \\ f_p(\boldsymbol{x}) < f_p(\boldsymbol{y}) \text{ for at least one } p \in \{1, 2, \cdots, M\} \end{cases}$$

The solution $\boldsymbol{x}$ dominates $\boldsymbol{y}$.

  - ■ Nondominated solution = Pareto-front (**PF**) solution
    : Any member of solutions that is not dominated by any other member

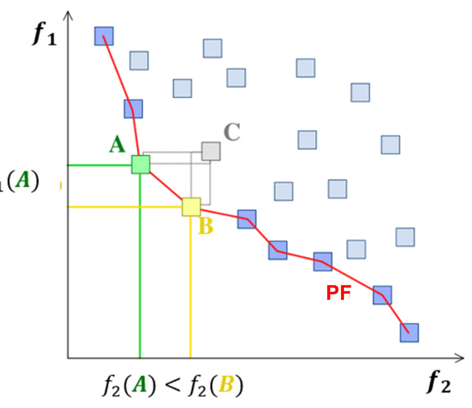


Fig. 1. Example of pareto-front solutions.

- ✓ Conventional MOO algorithms: NSGA-II, NSGA-III, MOEA/D, etc.

Applied MOO algorithm: NSGA-III

- ✓ Reference-point-based **N**ondominated **S**orting **G**enetic **A**lgorithm

[ref.] H. Jain and K. Deb, "An evolutionary Many-objective optimization algorithm using reference-point-based nondominated soring approach, part II: handling constraints and extending to an adaptive approach", *Evol. Comput.*, vol. 18, no. 4, pp. 6020-622, Aug. 2014.

- ✓ Handling three or more objectives (many-objectives) with constraints
- ✓ Optimization procedure

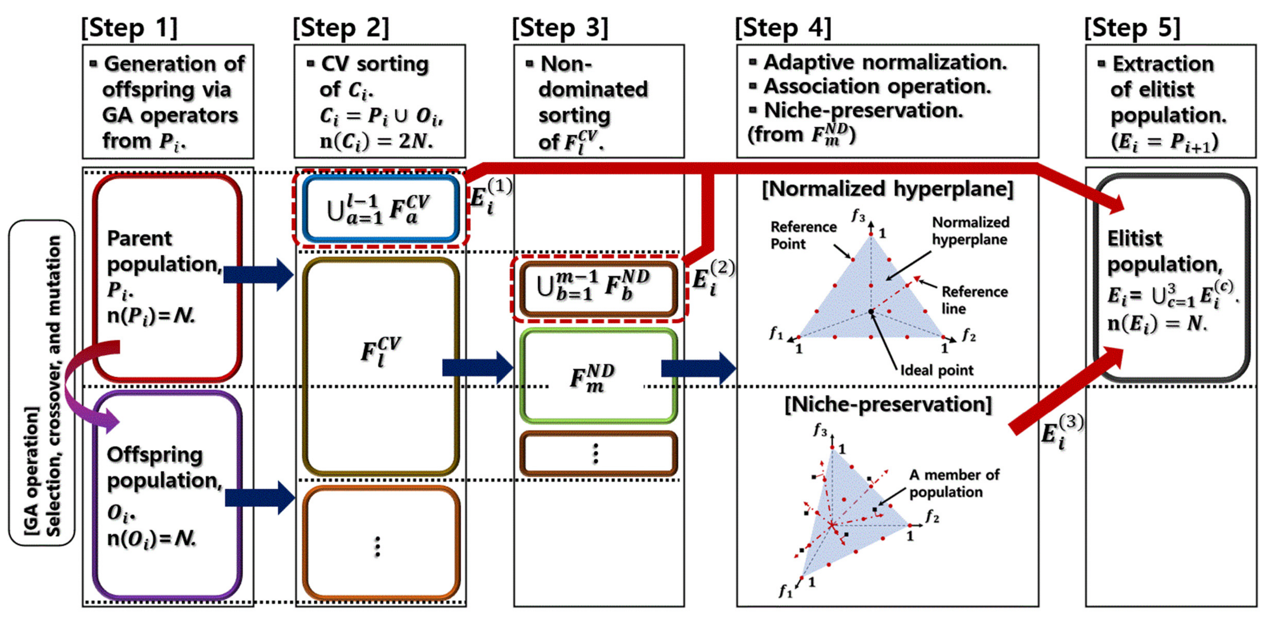


Fig. 2. Flowchart of NSGA-III algorithm.

■ Constraint Violation

$$\mathbf{CV}(\boldsymbol{x}) = \sum_{k=1}^{K} \langle \bar{g}_k(\boldsymbol{x}) \rangle + \sum_{l=1}^{L} \left| \bar{h}_l(\boldsymbol{x}) \right|,$$

$$\langle \gamma \rangle = \begin{cases} -\gamma, & \gamma < 0 \\ 0, & \text{otherwise} \end{cases}$$

$$w_k(\boldsymbol{x}) = w'_k(\boldsymbol{x}) - a_k \ge 0$$

$$\bar{w}_k(\boldsymbol{x}) = \frac{w'_k(\boldsymbol{x})}{a_k} - 1$$

III. Optimal Design of HTS Synchronous Motor

Specifications and design variables

Table I. Specifications

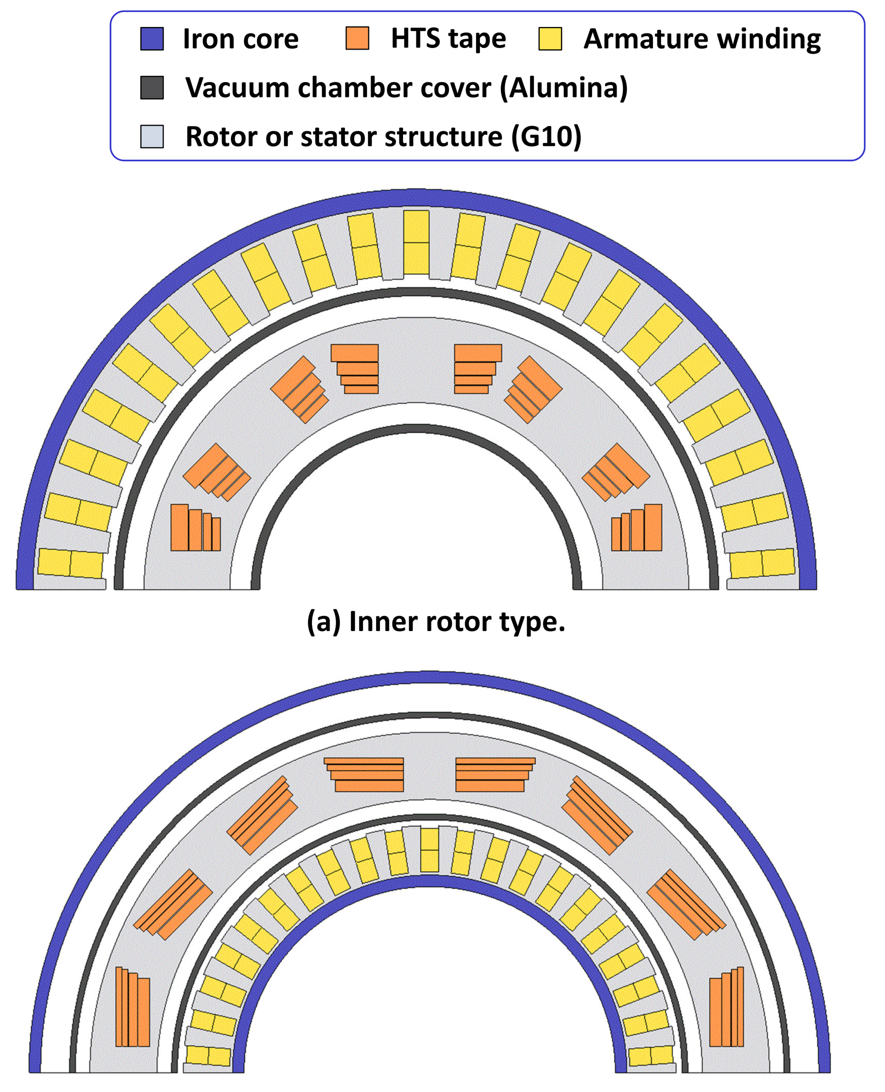
Item [unit]	Value
Rated power [kW]	200
Rated speed [rpm]	6000
Num. of phase / poles / slots	3 / 8 / 42
Armature coil fill factor	0.7
Armature current density [A/mm^2]	10
Inverter rated voltage [Vdc]	650
Operating temperature [K]	20
Num. of HTS tape stack	4
HTS tape thickness[1] [μm]	43
Critical current margin [%]	30

[1] 'REBCO 2G HTS wire' produced by SuperPower Inc. / https://www.superpower-inc.com/specification.aspx

Table II. Key design variables

Item [unit]	Value
HTS tape width[2] [mm]	2, 3, 4
Outer radius of rotor [mm] (Inner rotor type)	70 ~ 110
Outer radius of stator [mm] (Outer rotor type)	70 ~ 110
RS ratio = $\frac{\text{Outer radius of rotor}}{\text{Outer radius of stator}}$	Feasible range
LW ratio = $\frac{\text{Armature coil length}}{\text{Armature coil width}}$	Feasible range
Iron core thickness [mm]	2 ~ 10

[2] A multi-width approach is applied to improve motor performance.



(a) Inner rotor type.

(b) Outer rotor type.

Fig. 3. The design structure of HTS synchronous motor (180 deg).

Optimization problem and parameter

- ✓ 3 objective functions: $f_1(\boldsymbol{x}) = -SP(\boldsymbol{x})$, $f_2(\boldsymbol{x}) = -PD(\boldsymbol{x})$, $f_3(\boldsymbol{x}) = TC(\boldsymbol{x})$.
- ✓ Minimize $\boldsymbol{f}(\boldsymbol{x}) = \{f_1(\boldsymbol{x}), f_2(\boldsymbol{x}), f_3(\boldsymbol{x})\}$

  Subject to $h_1(\boldsymbol{x}) = T_{avg}(\boldsymbol{x}) - 318.5 = 0$

  $g_1(\boldsymbol{x}) = V_{ll,max}(\boldsymbol{x}) - 520 \le 0$

- SP: Specific Power [kW/kg]
- PD: Power Density [W/cm^3]
- TC: HTS Tape Consumption [km] (4mm equivalent)
- T_{avg}: Average Torque [Nm]
- $V_{ll,max}$: Max. line-to-line voltage of armature winding [V]

- ✓ NSGA-III parameter for optimization

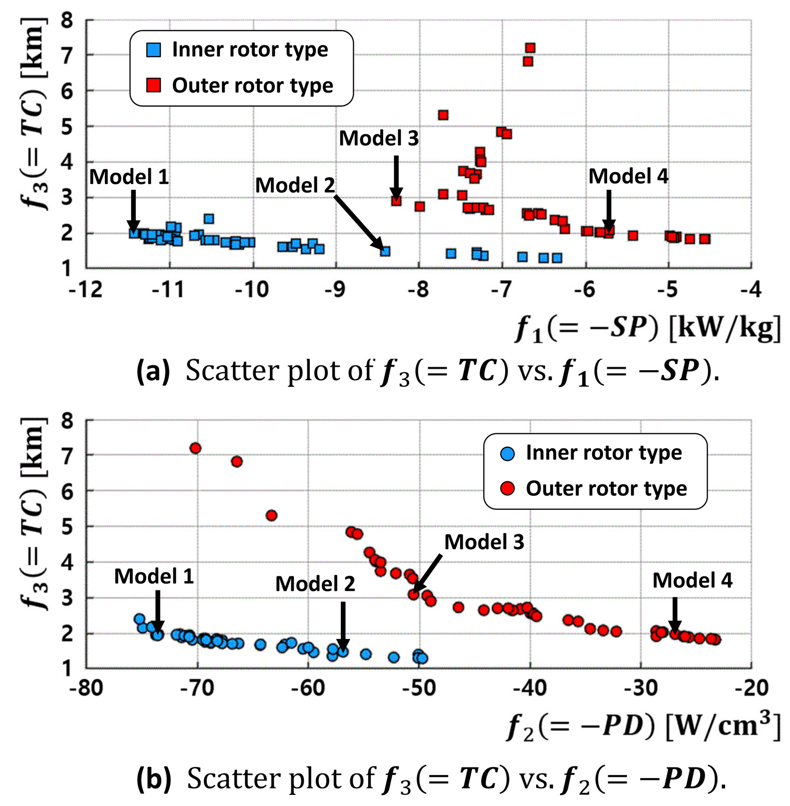
Table III. Optimization parameter

Item	Setting	Item	Setting
Population / Reference points	45 / 45	Selection operator	6-solution tournament
Convergence condition	80 generations	Crossover	Real-coded GA with SBX

- ✓ 2-D finite element method by 'JMAG designer' software is used.
- ✓ In-house 'NSGA-III code' is applied to the optimal design.

IV. Comparison of Optimized Results

Optimized result



(a) Scatter plot of $f_3(= TC)$ vs. $f_1(= -SP)$.

(b) Scatter plot of $f_3(= TC)$ vs. $f_2(= -PD)$.

Fig. 4. Optimized result of the HTS synchronous motor.

Table IV. Results of the optimized models

Item [unit]		Inner rotor type		Outer rotor type	
		Model 1	Model 2	Model 3	Model 4
Specific power [kW/kg]		11.4	8.41	8.27	5.73
Power density [W/cm^3]		73.7	56.9	49.0	26.9
HTS tape length [km] (4mm equivalent)		1.99	1.48	2.90	1.98
Total weight [kg]		17.5	23.8	24.2	34.9
Outer radius of rotor [mm]		91.5	74.7	82.2	98.0
Outer radius of stator [mm]		106.8	96.0	41.6	44.6
Stack length [mm]		75.8	121.5	75.0	119.0
HTS tape	width [mm]	2:2:2:3	2:2:2:2	3:2:2:2	2:2:2:2
	Turns per stack	456:435 :414:383	306:285 :264:238	607:586 :565:534	392:370 :349:328
	Critical current [A]	233	246	271	275
	Operating current [A]	163	172	190	192

[Conclusion]

In this paper, the inner and the outer rotor type of a partial HTS synchronous motor was optimized based on a multi-objective optimization. As a result of comparing three characteristics between the inner and the outer type of the HTS motor, the inner rotor type showed better results than the outer rotor type at the operating point (rated power and speed). Especially, a model with maximum specific power of 11.4 kW/kg was derived through the multi-objective optimization process in the inner rotor type of the HTS synchronous motor.