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Evolution strategies and multi-objective optimization of permanent magnet motor

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ABSTRACT

When designing a permanent magnet motor, several geometry and material parameters are to be defined. This is not an easy task, as material properties and magnetic fields are highly non-linear and the design of a motor is therefore often an iterative process. From an engineering point of view, we usually want to maximize the efficiency of the motor and from an economic point of view we want to minimize the cost of the motor. As these two things seldom go hand in hand, the goal is to find the best efficiency per cost. The scope of this paper is therefore to investigate the applicability of evolution strategies, ES to effectively design and optimize parameters of permanent magnet motors. Single as well as multi-objective optimization procedures are carried out. A modified way of creating the strategy parameters for the ES algorithm is also proposed and has together with the standard ES algorithm undergone a comprehensive parameter study for the parameters ρ and λ. The results of this parameter study show a significant improvement in stability and speed with the use of the modified ES version. To find the most effective selector for a multi-objective optimization, MOO, of the motor a performance examination of 4 different selectors from the group of programs called PISA has been made and compared for MOO of the efficiency and cost of the motor. This performance examination showed that the indicator based evolutionary algorithm, IBEA, and hypervolume estimation algorithm, HypE, selectors performed almost equally good on this MOO problem where the HypE selector only had a slightly better performance indicator.

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1. Introduction

Metaheuristics is used in combinatorial optimization in discrete and real search space by iteratively trying to improve the current best solution. There have been several proposed metaheuristic algorithms through time which can be used in optimization applications with some of the most commonly known being "hill climber", "TABU" [1,2], "simulated annealing" [3], "ant colony optimization" [4], "genetic algorithm" [5], and "evolution strategies" [6], to name a few. Metaheuristics, however, does not guarantee that the optimal solutions are ever found but there is a good possibility that a near optimal solution will be determined. This paper gives a theoretical contribution to the application of metaheuristics in the optimization of a permanent magnet motor, more specifically with the use of evolution strategies, ES. Several other authors have used evolutionary algorithms in the quest for optimization of PM motors where [7] optimize the rotor of a PM motor using genetic algorithms and [8] optimize an in-wheel motor using ES. Both articles use FEM in greater or lesser extent where this article will show the application of ES on analytical equations as FEA is very time consuming and therefore less suited for multi-objective optimization. ES has also been used by Chung and Kim [9] for the optimization of the pole shapes in a BLDC motor for reducing cogging torque where the present work will concentrate on a more global holistic approach. As one usually is not just interested in the optimization of one single parameter like [7–9] and a separate optimization of several parameters might not give a clear picture of the optimal combination of the parameters a multi-objective optimization has to be performed. No such multi-objective optimization based on the cost and efficiency of a PM motor has been found in the literature and is therefore investigated in this paper. The performance of 4 selectors is tested aiming at finding the one which is the most adequate for the problem of PM motor parameter optimization. Several authors also forget to mention in their works how the parameters for their algorithms have been chosen. In the present article, through an extensive parameter tuning, it will be shown that the parameter choice has a major impact on the final outcome like premature or slow convergence of the algorithms. The paper is divided into three main parts. The first part will describe the problem which has to be solved listing its object and fitness parameters. The second part will describe the algorithm of ES in detail and how its parameters have been tuned. This second

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Nomenclature

p	number of pole pairs
θ	temperature rise in the machine windings [K]
Matr	core material
$\sigma_{F_{tan}}$	tangential stress [Pa]
δ	physical air-gap [m]
Q	number of stator slots
a	number of parallel branches in coil
J_s	stator current density [A/m]
η	efficiency of the PM motor
Cost	cost of materials
μ	number of parent individuals
ρ	number of individuals for reproduction
λ	number of offspring individuals
g	generation number
$\mathfrak{P}_p$	parent population
$\mathbf{y}$	object parameter vector
$\mathbf{s}$	strategy parameter vector
$\mathbf{F}$	fitness value vector
$\mathfrak{E}_i$	marriage population
s_i	individual i's strategy parameters
y_i	individual i's object parameters
F_i	individual i's fitness value
$\mathfrak{P}_o$	offspring population
$\tilde{}$	mutated parameter
$\mathbf{a}$	individual parameter vector
$\mathbf{r}$	recombinant
σ	standard deviation
$\mathcal{N}$	random number from the standard normal distribution
τ_0	learning factor
τ	learning factor
c	proportionality factor
σ^2	variance
α	angle between object vectors
η_{max}	maximum efficiency of PM motor

part will only concentrate on the maximization of a single fitness parameter namely the efficiency of the motor. The third part will describe how to solve a multi-objective optimization problem with conflicting goals by combining ES and PISA where PISA is a group of programs which can be used for solving such multi-objective search problems where the conflicting goals in this problem as explained are the efficiency and the cost of the motor. At the end of the second and third part the findings from the ES algorithm and the motor parameters will be presented and commented on.

2. Parameter optimization of permanent magnet motor

Without getting into the details of how the efficiency of motor is calculated a short description of the motor design will take place. The procedure and equations for the underlying calculations of the motor efficiency can be found in the appendix and follows the approach described in [10]. In Fig. 1 a cross-section of a 3-phase 10-poles PM motor with 12 stator slots is shown where each stator slot contains coils from one or two of the phases as the number of slots divided by the number of poles is a fraction (fractional winding). These coils in the slots can consist of several parallel strains of copper conductors and the size of the stator slots is among other parameters dependent on the allowable current density in the copper conductors. Permanent magnets are mounted around the shaft in such a way that the magnets are magnetized alternately in opposite directions as to create north and south poles. The air gap in the

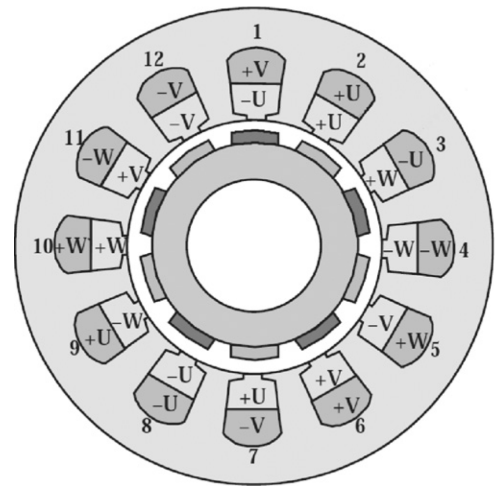

Fig. 1. Scematics of a PM motor [10].

Table 1
Object parameters.

Parameter	Valid range	Unit	Description
p	$[1–6] \in \mathbb{N}$	–	Number of pole pairs
θ	$[60–100] \in \mathbb{R}$	°K	Temperature rise in the machine windings
Matr	$[1, 2, 3] \in \mathbb{N}$	–	Core material
$\sigma_{F_{tan}}$	$[20e3–50e3] \in \mathbb{R}$	Pa	Tangential stress
δ	$[0.001–0.020] \in \mathbb{R}$	m	Physical air-gap
Q	$[20–50] \in \mathbb{N}$	–	Number of stator slots
a	$[1–60] \in \mathbb{N}$	–	Number of parallel branches in coil
J_s	$[4e6–6.5e6] \in \mathbb{R}$	A/m	Stator current density

motor is the gap between the surface of the magnet and the stator inner diameter where this inner diameter is determined by the maximum allowable tangential stresses in the motor. As it would be a huge task to take all design parameters into account in this optimization analysis, some of the parameters have been fixed at reasonable values. Some of these fixed values are the shaft power, the speed of the motor, line to line voltage, number of phases and are normally determined by the costumer of the motor and specified to match their needs. For getting a complete list of the fixed values we refer to the first table in Appendix. Table 1 shows the object parameters which will be used in this analysis and are the motor variables that can be changed in the search for an optimal design. Most of these parameters have already been explained except the temperature rise which has an influence on the resistance of the conductors and the choice of material which have different magnetic properties. The different parameters valid range come from the literature and "rules of thumb" [10–13]. The fitness values for this optimization problem are the efficiency and the cost of the motor and are kinds of grade explaining the goodness of a specific combination of object parameters. The fitness values are listed in Table 2. The fitness function **F** is a function which in the following will be considered a black box and calculate the efficiency and cost of the motor as a function of the object parameters. The fitness function is basically all the equations listed in the appendix

Table 2
Fitness parameters.

Parameter	Description
η	Efficiency of the PM motor
Cost	Cost of materials

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