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Particle swarm and Box's complex optimization methods to design linear tubular switched reluctance generators for wave energy conversion

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ABSTRACT

This paper addresses the optimization of the linear switched reluctance generator with tubular topology to be applied in a sea wave energy conversion system. Two new algorithms to optimize the geometry of the generators are proposed. The algorithms are based on both particle swarm and Box´s complex optimization methods. The optimization procedures consist of a multidimensional optimal value search. First the initial variable vectors are specified throughout the feasible search space. Then, an iterative procedure is applied with the goal of finding the variable values that minimize the objective function. The proposed algorithms are suitable for the optimization problem considered since the objective function is highly nonlinear and not analytically defined, as evaluated using a finite element analysis based software, and show very good performance. A factor that characterizes the generation capabilities is also defined and the obtained optimized generators are compared.

1. Introduction

The switched reluctance machine (SRM) is a device characterized by the absence of permanent magnets in its configuration, a simple construction with low manufacturing costs, high reliability and strong fault tolerance capability when compared to other types of electric machines [1]. The SRM is composed of a static part (stator) and a movable one, with the electric phase windings usually housed in the static part. The movable part (rotor for a rotary type machine or translator in the case of a linear type) is free of permanent magnets, excitation windings or other sources of magnetic field, which leads to a low inertia machine with a very fast actuation response. Its operation as a generator is only distinguished by the control strategy, whereby different commutation periods are applied to the electronic switches of the power converter [2]. The electric phases are excited establishing a magnetic flux whose intensity is decreased when the translator, driven by an external force, is forced to occupy the position of maximum reluctance.

The idealized electromagnetic characteristics corresponding to the minimum and maximum reluctance (maximum and minimum values of inductance L_{max} and L_{min}, respectively) are defined by the relative position of the translator with respect to the stator. In opposition to the decreasing magnetic flux linked by a given phase, an electromotive force is developed in the phase windings terminals generating electric energy when connected to an electric load.

The majority of the literature available for this type of electric machine is directed towards rotary machines [3–5]. Linear switched reluctance generators for direct drive conversion systems with flat and tubular topologies have been proposed and analysed [6–8]. The generation capability of a SRM depends on the velocity of its movable part and on the rate of change of the machine's inductance with its relative displacement. The first factor relies on the nature of the external force that drives the generator and, consequently, imposes the operation velocity. Thus, for generators applied in sea wave energy conversion systems the wave height, mean and peak periods and also the wave direction distributions are the main design parameters [9,10]. The second factor relies on the geometric configuration of the machine, which can be controlled, during the project, in order to maximize its generation capabilities. For this reason choosing the best dimensional parameters is very important. However, when the number of variables is high, it becomes unpractical to perform the design procedure with all possible value combinations. To avoid this exhaustive process, optimization methods are applied to reduce the search for the optimum values. In general, electric machine optimization is

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characterized by non-linear problems with objective functions depending on a large set of variables. For functions with more than 3 variables, it is impossible to map its evolution with the respective variables and thus to identify the location of its maximum (or minimum) values. For these reasons, the application of methods that imply a continuum evaluation of the objective function gradient (gradient method) is discarded, because they can become trapped in local maximum (or minimum), depending on the initial conditions, and because they need to perform additional function evaluations which, in these problems, are the most time and resource consuming steps.

Global optimization methods are an alternative approach to exact methods and are based on deterministic or stochastic procedures to perform the search. In deterministic methods, a direct search of values is conducted according to the function evolution. Stochastic methods are supported by decisions based on random and/or probabilistic parameters. The latter methods are, usually, based on the behavior and evolution of living communities, and were, already, used in the design optimization of electric machines [11,12].

A stochastic method that is commonly used for this type of optimization problem is the Particle Swarm Optimization (PSO) that simulates the behavior of populations (like a flock of birds) in search for food.

Compared to other artificial optimization techniques, as for example Genetic Algorithms (GA), PSO has some important advantages as for example its easy implementation, the few parameters to be adjusted, the absence of evolution operators, the updating of the particles with the internal velocity, the information given by the 'best' particle to the others, etc. Thus, this method tends to converge to the best solution quickly, and is a very good method to be applied in the design optimization of structural models. PSO has been proposed for the design of switched reluctance machines [13,14].

Box [15] proposed another optimization method, the Box Complex Method. This method has been used previously and applied to constrained optimization problems, and appears to be more effective in certain cases. It is relatively easy to implement and is well suited for non-linear problems having inequality constraints. Some authors have shown that the Complex Method can be used in electromechanical devices for different purposes [16,17].

We propose two new algorithms to optimize the geometry of different structural configurations of linear switched reluctance generators with tubular topology to be applied in a sea wave energy conversion system. The algorithms are based on both particle swarm and box complex optimization methods. These optimization methods consist of a multidimensional optimal value search that is initiated by specifying initial variable vectors throughout the feasible search space. Starting with these initial variable vectors, an iterative procedure is applied with the goal of finding the values that minimize the objective function and the search is only concluded when the maximum allowable iteration number is achieved or the specified convergence criteria are met. The two algorithms differ in the computational iterative technique used to find the best solution that can be achieved during the optimization process, without guarantee of finding the global optimum. The main advantage of these two optimization algorithms resides in the fact that only the function value of the variable vectors is needed to conduct the iterative search, thus discarding the calculation of the function gradient or other intermediate procedures. This advantage makes these algorithms suitable for the optimization problem presented, since the objective function is highly nonlinear and not analytically defined, as evaluated using finite element analysis based software. Thus, bypassing the calculation of a numerical gradient is of great interest to minimize the number of function evaluations and, consequently, the optimization time. In addition, we compare the generation capabilities of the resulting optimized generators.

2. The optimization problem

The optimization problem is meant to find the values of certain geometrical parameters that maximize the electric generation capabilities of two structural models of a switched reluctance generator. To quantify the capability of each structural model as electric generator, the electromotive force that each model can develop at the electric phase windings is given by [18]:

$$e = vi\frac{dL(i,x)}{dx} \tag{1}$$

As expressed in (1), the electromotive force e is proportional to the translator (movable part of the generator), to the velocity v, to the phase electric current (i) and to the rate of change of the machine's inductance with its position $\frac{dL}{dx}$. The translator velocity does not depend on the structure of the generator but, instead, on the nature of the external force that drives it. As for the electric current, this parameter usually has a specified maximum value due to hardware limitations and, consequently, shall not be further increased.

Thus, for a fixed electric current value, the potential of each structural model may be evaluated by the rate of change of the machine's inductance with its position because the inductance is an electromagnetic characteristic that depends on the structural configuration of the electric generator. For different relative positions of the translator, with respect to the stationary part of the generator (stator), the generator will assume distinct configurations with particular values of inductance. Therefore, each structural configuration will present inductances between a maximum and a minimum value. The greater the difference between the value of inductance in the alignment position L_a and the inductance value in the unaligned position L_u, the greater the electromotive force developed at the terminals of each electric phase of the generator for a given velocity of the translator. Likewise, the lower the distance Δx the translator must travel between these two alignment conditions, the greater the developed electromotive force. However, these machines are characterized by non-linear magnetic characteristics, especially for high electric currents. Due to the complexity in accounting for the rate of change of inductance with the translator position in non-linear operating conditions, an ideal case was assumed in order to characterize the generation potential subjacent to each structural model during the optimization process. This idealization implies a linear assessment of the electromagnetic characteristics of the electric machine. The generation capabilities for each generator will be accounted for by the factor Q, which represents the linear rate of change of the inductance with the translator's position between aligned and unaligned positions:

$$Q = \frac{L_a - L_u}{\Delta x} \tag{2}$$

The factor Q, given by expression (2), is the objective function that should be maximized for each model, given the variation of a set of dimensional parameters that defines the geometry of the respective structural model. Therefore, for each geometric configuration under assessment, the optimization problem is defined