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Optimal design of permanent magnet flux switching generator for wind applications via artificial neural network and multi-objective particle swarm optimization hybrid approach

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ABSTRACT

In this paper a new hybrid approach obtained combining a multi-objective particle swarm optimization and artificial neural network is proposed for the design optimization of a direct-drive permanent magnet flux switching generators for low power wind applications. The targets of the proposed multi-objective optimization are to reduce the costs and weight of the machine while maximizing the amplitude of the induced voltage as well as minimizing its total harmonic distortion. The permanent magnet width, the stator and rotor tooth width, the rotor teeth number and stator pole number of the machine define the search space for the optimization problem. Four supervised artificial neural networks are designed for modeling the complex relationships among the weight, the cost, the amplitude and the total harmonic distortion of the output voltage respect to the quantities of the search space. Finite element analysis is adopted to generate training dataset for the artificial neural networks. Finite element analysis based model is verified by experimental results with a 1.5 kW permanent magnet flux switching generator prototype suitable for renewable energy applications, having 6/19 stator poles/rotor teeth. Finally the effectiveness of the proposed hybrid procedure is compared with the results given by conventional multi-objective optimization algorithms. The obtained results show the soundness of the proposed multi objective optimization technique and its feasibility to be adopted as suitable methodology for optimal design of permanent magnet flux switching generator for wind application.

1. Introduction

The perpetual increase of wind turbine power generation from small scale (kW class) sizes to large scale (MW class) indicates the importance of electrical generators in wind turbine conversion systems [1]. In the literature the state of the art of each component of the wind energy conversion system has been widely analyzed [2]. Different type of generators have been investigated in many studies where doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) are counted as the most popular ones for wind power applications. The design of DFIG for maximizing specified characteristics is proposed in [3]. The performance of DFIG under different control strategies has been developed too. In particular a control algorithm considering adaptive model reference approach for maximum power point tracking (MPPT) is proposed in [4]. In [5], in order to prove the superior performance of the geometrical approach, sensorless control, based on high order sliding mode of the DFIG has been suggested. The impact of the DFIG on power system dynamic behavior has been analyzed in [6]. The power optimization of a wind energy conversion system connected to the grid according to its control strategy has been covered in [7]. Standalone operations of DFIG in remote power supply with MPPT control method was investigated in [8]. Meanwhile, an advanced control strategy during grid faults was introduced in [9]. Also the studies regarding PMSG are very diffused. In [10] MPPT and optimal torque control method have been adopted for extracting and exploiting the maximum power from the PMSG and for feeding the grid by high-power and good electrical energy quality. The design of a fault tolerant controller based on an adaptive Luenberger observer with the aim to enhance the robustness of the wind conversion system with PMSG has been investigated in [11]. In [12] a hybrid scheme employing direct torque control based on fuzzy controller supervisor is discussed. Moreover in [13] a new selective harmonic elimination technique

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Nomenclature

g	air–gap length
y_j	j-th neuron of the output layer
N_h	number of the neurons of the hidden layer
N_i	number of the neurons of the input layer
c_1, c_2	acceleration constants in PSO algorithm
$rand_1$, $rand_2$	uniformly distributed random values in a range [0,1]
N	number of particles in a swarm

is developed for a PMSG with a multilevel inverter to reduce the total harmonic distortion of the output voltage. A standalone system including diesel-PMSG based on fuzzy control is suggested in [14]. In [15] current sensor fault diagnosis for a PMSG drive is considered. Fifth harmonic and sag impact on PMSG are investigated in [16].

Also the design aspects of a PMSG are widely treated. For instance, a new solution for minimizing cogging torque of the PMSG is developed in [17]. Fractional slot concentrated winding (FSCW) method for reducing magnetic saturation is studied in [18]. Meanwhile design analysis and experimental verification of a radial PMSG is conducted in [19].

The interesting features brought by PMSGs provide the opportunity to introduce new types of generator (Permanent magnet flux switching generator, PMFSG) with much more advantages. In this machine the PMs and the windings are located in the stator of the machine and rotor is a passive part containing only stainless steel structure [20]. This property provides possibility to easily utilize the permanent magnet flux switching machine (PMFSM) in many applications ranging from low to high speed rotation. PMFS machine utilization for a high reliability application is proposed in [21]. The feasibility of PMFS machines for hybrid vehicle application was thoroughly investigated in [22] where the performance of the PMFSM was compared with available IPM machine. In-wheel light traction is another application where the performance of the PMFSM is underlined in [23]. Moreover a solution for improving PMFSM performance for high speed applications is proposed in [24]. At last in [25] PMFSM for downhole use is presented. Recently, because of its outstanding features, PM flux switching generator is introduced also as a proper candidate for direct drive wind turbine systems. A 12/10 axial field PMFS (AFPMFS) doubly salient structure for wind power system is presented in [26]. Different configurations and stator pole combinations have been analyzed and compared with conventional PMSG machines in [27]. The improved design of PMFSM to increase torque and power was pursued in [28]. Static characteristics analysis has been investigated in [29]. In addition, the design optimization of a PMFSM in order to attain maximum output torque was carried out in [30].

PMFSG is the resultant of combining brushless permanent magnet and switched reluctance machines (SRM). Hence, it benefits by the advantages of both the mentioned type of machines. In particular the high torque and power density properties of the PMSG [19] are combined with the rigid structure and fault tolerant capabilities arising by the SRM machines [31]. The results show that the rigid structure of the PMFS machine, due to the position of PM in the stator and simple structure of the rotor may bring about bright future, especially for wind turbine applications [32].

The fault tolerant capability leads to continuous operating mode during fault condition which is obviously owing to SRM features and it is due to detachment of magnetic and electric circuit of the machine [33]. Furthermore, the benefits of PMFS generator, such as smaller size and weight as well as more reliability and efficient performance in comparison with conventional synchronous and induction generators lead to allocate much more study for PMFS machines [34]. The main drawback of the PMFSG is directly dependent on the electrical frequency to rotor pole number. This could limit the design procedure in high speed application that ultimately effects on power loss and efficiency of the high speed machine [21]. Moreover other disadvantages are relatively high cogging torque amplitude and, often, unbalanced magnetic force causing mechanical fatigue and finally a non adequate total harmonic distortion of the induced voltage [32]. These considerations can explain the interest in developing optimal methods for the design of this type of machine [27]. Nevertheless, the design of a low power PMFS machine is a classical issue that involves trade-offs among more conflicting targets. Typically, it is desired to minimize costs and mass of the machine while maximizing electromagnetic performance. For such type of problems, the classical methods of the mathematical optimization fail, because there are multi objective functions to maximize (or minimize) and there is no single solution that can simultaneously optimize each objective. Therefore, much attention is paid to Pareto optimal solutions, namely, solutions that cannot be improved in any of the objectives, without degrading at least one of the other objectives. At the moment the literature does not present any works about multi-objective design optimization of PMFS machines. On the contrary, in literature different papers have been devoted on scalar optimization referred to PMFS or other categories of PM machines. Genetic algorithm (GA) is developed for topology optimization of the stator teeth in a brushless DC motor in [35]. In [36] optimal design of interior permanent magnet synchronous (IMPS) machine is developed based on combination of GA and mesh adoptive guided search. An adaptive neuro-fuzzy approach for PMSG is presented in [37]. As one of many available optimization methods, response surface and differential evolution is employed for design optimization tools of an electrical machine in [38]. Recently, also particle swarm optimization (PSO) approach has been used for design purpose [39]. Many interesting advantages push toward the use of this technique. As it is well known not only PSO is largely affected by the non linearity of the problem but it has also less parameters to adjust and so it can be conveniently combined with other techniques to form hybrid tools [40]. Moreover the algorithm does not use a gradient in the course of the optimization and for this reason, it can be successfully used in different optimization problems (irregular, variable in time and so on). Anyway, for extending the PSO to solve multi-objective problems and to make a Multi-Objective Particle Swarm Optimization algorithm (MOPSO), some arrangements are needed, as it will be referred in this work.

In the paper, a new hybrid approach composed by artificial neural networks (ANN) and by multi-objective particle swarm optimization for the optimal design of a direct-drive permanent magnet flux switching generators is proposed. There are different papers in literature where PSO is combined with ANN for optimization purpose, however, the proposed method, combining MOPSO and ANN for optimization used in this study, makes it different from the others.

The optimization procedure can be resumed in two main steps: in the first step supervised artificial neural networks are trained for modeling the complex relationships between the optimizing variables and the selected design variables; the training and the