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Parameter optimization and speed control of switched reluctance motor based on evolutionary computation methods

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ABSTRACT

Because of the double–salient structure and switching mode of switched reluctance motor (SRM), it is very difficult to acquire the analytical model for the SRM. The current-sharing method (CSM) is an effective inner-current loop designing strategy, which makes the high performance control of the SRM become possible without application of its mathematical model. However, there are six control parameters that need to be tuned in the CSM. If the PID controller is adopted in the speed loop, there will exist nine parameters that need to be tuned in the speed control of the SRM. It is a challenge work to tune nine parameters with manual trial-and-error method. To alleviate the difficulties of the parameter tuning for the SRM control, three types of evolutionary computation methods are applied in the parameter optimization of the SRM, which include differential evolution (DE) algorithm, Big Bang–Big Crunch (BBBC) algorithm and particle swarm optimization (PSO). The comparison of the optimization performance among the proposed evolutionary computation methods are demonstrated with Matlab simulation. Simulation results certify the feasibility and effectiveness of the proposed methods in the parameter optimization and speed control of the SRM.

1. Introduction

Switched reluctance motors (SRMs) are essentially different from induction motors (IMs) and permanent magnet synchronous motors (PMSMs) in working principles [1–3]. The rotor of the SRM need not any permanent magnet or windings. The SRMs have many preferred characteristics, such like simple structure, high ruggedness, low cost, fast dynamic response and big overload capability. The SRMs have become potential candidates with strong competition ability in many motor driving fields [4–7]. Because of the double–salient structure in design, high saturation of the magnetic field in working and switching mode of the converter in control, the SRMs are very complex electromagnetic systems and have highly nonlinear features, which make the SRMs have large torque ripple and acoustic noise. To suppress the torque ripple, the traditionally adopted methods mainly include torque-sharing function method (TSF) [8–10], direct instantaneous torque control (DITC) [11,12], direct torque control (DTC) [13] and current profile strategy [14]. All the above torque suppression strategies need the computation of the electromagnetic torque or the flux linkage of the SRM. It is well known that the electromagnetic torque and the flux linkage of SRM are the functions of the phase current and the rotor position. Until now, the researchers still did not find the widely accepted analytical model that can describe relationship of the electromagnetic torque or the flux linkage with the phase current and the rotor position of the SRM.

At present as we know, to realize the high performance control of the SRM, constructing an accurate model is the first step that is often adopted. In the SRM, there exist three important nonlinear relationships, which are the electromagnetic torque (T), inductance (L) or flux linkage (Ψ) with the phase current (i) and the rotor position (θ). To achieve the modeling of the SRM, one of the three relationship is necessary to be constructed. In [15–18], the relationship of $\Psi - i - \theta$ was constructed, where the parameters of geometry, number of turns, or some characteristics of the magnetic material were required. In [19–21], the relationship of $L - i - \theta$ was firstly acquired, and then T or Ψ could be computed through the relationship between L and T or Ψ. In [22,23], the relationship of $T - i - \theta$ was obtained, where very complex position function was used. Although the above literatures acquired the analytical relationships for the SRM, their defects are very distinct. And these defects in modeling of the SRM can be summarized as the following four aspects.

(1) The present SRM models are constructed based on special requirements. These models have their limitation in the applications. And the models are lack of the adaptiveness in different circumstances.

(2) The modeling procedure of the SRMs has many complex computation. And this will make the realization become very difficulty and increase the computation workload of the controller.

(3) Some modeling methods require the parameters of the material

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or geometry. And because of the manufacture or measurement errors, the errors will reduce the accuracy of the model. In addition, some parameters of the material or geometry are difficult to obtain for the general users.

(4) For the SRMs with huge volume and large power, it is almost impossible or very expensive to acquire the model through experiment.

Because of the above existing defects, it is very meaningful to find the control methods for the SRM without the modeling procedure. In [24], an off-line torque-ripple reduction scheme using a neuro-fuzzy compensation mechanism was presented. The applicability of the proposed method was restricted due to the need for an off-line training and the use of a torque sensor. In [25], a novel concept of digital control with low and high variable states was presented for speed control of the SRM. The reference current was perturbed by the previous reference current as a function of the sign and the magnitude of the speed error. Although the speed control of the SRM can be realized without the modeling procedure in [24,25], the torque ripple of the SRM is a bit large in a definite range compared with the TSF method. In [26,27], a novel current-sharing method (CSM) was proposed to realize the speed and position control of the SRM without the model information besides the phase number. From the design of the CSM, it can be seen that there exist six parameters that need to be tuned. It is a challenge work to tuning the parameters of the CSM with manual trial-and-error method. This paper will adopt evolutionary computation methods to optimize the parameters of the CSM, which can alleviate the tuning difficulty of the parameters.

Evolutionary computation methods originate from the natural selection to realize the iterative optimization in a population. The population is guided with random search to achieve the desired objective. Evolutionary computation methods belong to derivative-free optimization and include genetic algorithm (GA) [28], ant colony optimization (ACO) [29], particle swarm optimization (PSO) [30,31], differential evolution (DE) [32,33], Big Bang–Big Crunch algorithm (BBBC) algorithm [34] and so on. In [35], an elitist-mutated multi-objective particle swarm optimization (EM-MOPSO) was used to tune parameters of PI speed controller, turn–on and turn–off angles. The PSO optimization could enhance the speed and torque control performance for the SRM. In [36], two new algorithms to optimize the geometry of the linear switched reluctance generator are proposed, which are based on both particle swarm and Box's complex optimization methods. In [37], a control mechanism for speed control of SRM with torque ripple reduction using non-dominated sorting GA (NSGA-II) was presented. The optimum values of proportional and integral gains for both speed and current controller along with the turn–on and turn–off angles were obtained. In [38], a genetic algorithm is utilised to optimize the original design model for efficiency and reduced volume of one 1 kW SRG. In the control or design optimization, GA and ACO have many limitations, such like the large computation complexity and slow convergence speed. Compared with GA and ACO, DE, BBBC, and PSO have less control parameters and have larger application potentialities. The prominent advantages of the DE, BBBC and PSO are given as the following three aspects, respectively.

(1) The advantage of the DE comes from the mutation with difference vectors, which increase the convergence speed of the DE in shallow region. The DE algorithm can be realized with a few lines of codes with concise design structure. And the optimization efficiency of computation is very high.

(2) The BBBC generates random points in the Big Bang phase and shrinks to a single point step by step in the Big Crunch phase. Simplicity and effectiveness are its very important merits, which make the BBBC a very potential evolutionary computation method.

(3) The advantage of the PSO originates from the population tracking of local and global optimum points in the optimization space. High optimization speed is also one of the merits of the PSO.

In general, no evolutionary computation method has been turned out to be the best for all the optimization. Each optimization has its perfect application area. In this paper, the parameter optimization speed is the most important aspect for the control of the SRM, other optimization method, such like GA and ACO are not suitable. Therefore DE, BBBC and PSO will be used in the parameter optimization and speed control of the SRM. And the optimization results are compared to show the effectiveness of the proposed methods in the parameter optimization for the speed control of the SRM.

The organization of this paper is given as following sections. Section 2 introduces the details of the CSM for the SRM and the problems that exist in the design of the CSM. Section 3 gives the design procedure of three types of evolutionary computation methods. Section 4 shows the optimization results with proposed evolutionary computation methods. Section 5 gives some discussions on the optimization and control of the SRM. And at last, some conclusions are summarized in Section 6.

2. Introduction of the CSM

According to the interaction of the stator and rotor, the motors can be mainly divided into double-side and single-side magnetizing motors. Direct current motor (DCM), brushless direct current motor (BLDCM) and PMSM have magnetic fields that are produced by the rotor and stator respectively. These motors belong to the double-side magnetizing motors. The IM and the SRM have magnetic fields that are produced by the stator (the rotor magnetic field of the IM is inducted by the stator magnetic field). They belongs to the single-side magnetizing motors. There exist more difficulties in the control of the single-side magnetizing motors than that of the double-side magnetizing motors. Field orientated control (FOC) or direct torque control (DTC) can effectively solve the control of the IMs. It has been proved that there does not exist a decoupling method like the FOC for the IM that can realize the decoupling control for the SRM. The novel CSM can decouple the phase current in the stationary frame for the SRM. It has some similar function with the FOC from the point of the current control.

In this paper, the target SRM is a four-phase 8/6 SRM. The data of the SRM are given in Appendix. Fig. 1(a) shows the distribution of the stator windings of the SRM in the space. The distribution of the phase current and flux-linkage space vectors of the SRM is shown in Fig. 1(b). From Fig. 1, we can obtain the following three principles for the SRM.

(1) The symmetrical distribution of the stator windings (AA', BB', CC' and DD') of the SRM makes the phase current space vectors (i_a, i_b, i_c and i_d) distributed symmetrically in the vector space. And the latter vector is delayed with the former vector with 90° electrical degrees.

(2) The phase flux-linkage space vectors (Ψ_a, Ψ_b, Ψ_c and Ψ_d) are in the same direction with their phase current space vectors (i_a, i_b, i_c and i_d), respectively. And the phase flux-linkage space vectors are also distributed symmetrically in the vector space.

(3) The current or flux-linkage vector of phase A is oppositive with that of the phase C, and the current or flux-linkage vector of phase B is oppositive with that of the phase D. It is preferred that phases A and C,

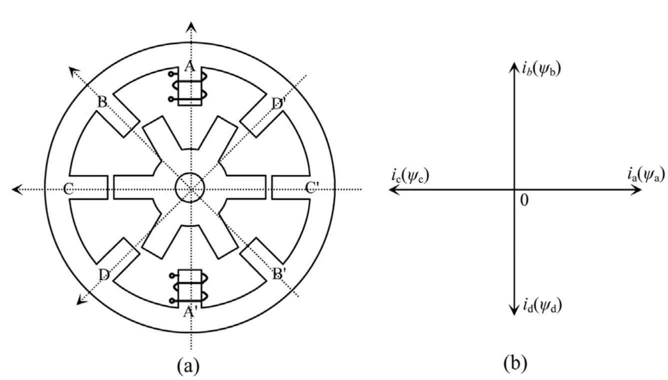

Fig. 1. (a) The stator windings. (b) The distribution of current and flux-linkage vectors.