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Research article

Levitation control of an improved modular bearingless switched reluctance motor

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ABSTRACT

In order to reduce coupling between torque and suspending force in conventional bearingless switched reluctance motor (BLSRM), one 12/12 hybrid-stator-pole structure BLSRM was investigated. In this structure, motor consists of two single phase motor. Biased flux is provided by axial permanent magnet, which is installed between two motor in axial direction. However, axial permanent magnet occupies axial space, which results in increased axial length and decreased critical speed. Therefore, an improved modular BLSRM is proposed in this paper. In order to reduce axial space and improve critical speed, permanent magnet is designed to install in stator yoke. To realize steady levitation during rotor rotating, one simple levitation control strategy is put forward, which is benefitted from natural decoupling between torque and suspending force. In addition, digital control system including torque and suspending force is designed by means of TMS320F28335 and experimental platform is established. Finally, the improved BLSRM can be steadily levitated in the static and rotating conditions by experimental results.

1. Introduction

As well known, switched reluctance motor (SRM) has an excellent performance under special environments, because of inherent fault tolerance, robustness, tolerance of high temperature [1–3]. In the meanwhile, magnetic bearing has some advantages such as no friction, no lubrication and long life, which is suitable for the high speed application. Combining advantages of SRM and magnetic bearing, bearingless SRM was proposed. Compared with conventional separated magnetic levitation motor, bearingless SRM highly integrates motor and magnetic bearing [4]. It means that motor not only supplies rotating torque but also provides levitation force. Therefore, bearingless SRM is particularly suitable to operate in special environments such as blood pump [5].

Recently, several structures of bearingless SRM have been proposed. A radial force and torque control scheme was proposed for bearingless control of a 12/8 pole SRM which has auxiliary windings for radial force in stator poles [6]. Additionally, an independent control strategy of average torque and levitation force was presented. In this method, current calculating algorithm was deduced to minimize the magnitude of instantaneous torque in the levitation region [7]. In the meanwhile, the least magneto-motive force strategy has been investigated to enhance the availability of winding currents and decrease the torque ripple and stator vibration [8]. Chen et al. analytically computed winding currents to generate torque and levitation force for a bearingless SRM [9,10]. In this method, three windings are loaded with different currents in each commutating period and three torques and three lateral forces can be generated. According to the published papers, one common problem in the above structures is that there is strong coupling between torque and radial force. Because of inherent principle of torque and radial force in conventional SRM, this overlap region is very narrow as shown in Fig. 1. The operating point has to be selected to compromise between torque and suspending force. Consequently, regions for torque and radial force cannot be fully utilized. Current has to be increased and dwell angle should be moved toward aligned position for achieving enough suspending force. It means that either of torque and suspending force can increases with the expense of larger current value, higher copper loss and thermal problem. On the other hand, torque and suspending force are simultaneously generated by the same winding current, and they are the nonlinear functions of current and position. Therefore, it is very difficult to decouple the torque from suspending force.

In order to reduce coupling through modifying motor structure, hybrid stator poles concept structure has been proposed such as 8/10 and 12/12 [11,12]. In this structure, torque pole on the stator generates torque while radial force pole generates suspending force. However,

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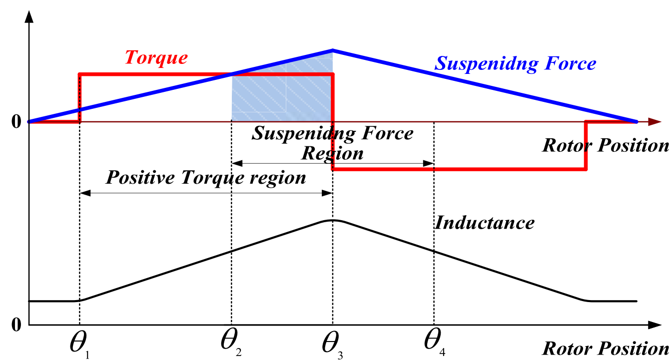

Fig. 1. Torque and suspending force in conventional bearingless SRM.

when these two types of stator poles are simultaneously working, magnetic crossing between fluxes by these two poles is hardly avoided in 8/10. In addition, motor consists of two single phase motor in 12/12 structure. Biased flux is provided by axial permanent magnet, which is installed between two motor in axial direction. However, axial permanent magnet occupies axial space, which results in increased axial length and decreased critical speed. Furthermore, power density is low due to single phase motor.

Therefore, an improved modular bearingless SRM is proposed to reduce axial space and produce higher torque [13]. Although motor structure and suspending principle has been briefly introduced and basic control diagram has been simply implemented by some experimental results, disadvantages of previous motor structure and advantages of proposed motor have not been compressively analyzed. Moreover, to achieve good suspending force performance, detailed modeling for suspending force and control algorithm are necessary. Anyway, these are not presented in Ref. [13]. Additionally, related experimental results, which verify advantages of proposed motor, are absent. To clarify advantages and describe novelty of proposed structure, in this paper, operating principle for proposed structure and mathematic model for suspending force are described. In the meanwhile, one simple levitation control strategy is presented to realize steady levitation during rotor rotating. Moreover, digital control system including torque and suspending force is designed by means of TMS320F28335 and experimental platform is established. Proposed bearingless SRM can be steadily levitated in the static and rotating conditions by experimental results.

2. Improved modular bearingless SRM

2.1. Basic structure

As shown in Fig. 2, it can be seen that improved modular bearingless SRM has 12/14 structure. It has four suspending T core stator poles and four C core torque stator poles, in which two cores is magnetically separated by nonmagnetic material. Between adjacent suspending poles, one permanent magnet (PM) is installed in stator yoke to provide biased flux for suspending force. In the meanwhile, control windings in opposite diameter direction such as X1&X2 and Y1&Y2 are connected in serial and installed on the suspending poles, which provide control flux to regulate levitation force in x- and y-direction, respectively. In order to reduce magnetic reluctance of control flux path, a second air-gap is employed, which located under PM. Additionally, torque windings such as A1&A2&A3&A4 are installed on the torque pole and connected in serial to form one phase for generating torque.

2.2. Operating principle

In order to show operating principle of proposed structure, levitation force in y-direction is taken for example as shown in Fig. 3. It can be found that biased flux provided by PM goes through stator yoke, suspending pole, air-gap, rotor and back to PM, as shown in solid purple line. When rotor is at center position, flux densities of upper and lower part air-gap supplied by PM are same. However, when rotor is eccentric from center position to y-positive direction, control winding is conducted and control flux is generated, as shown in green dot line. And then, under action of biased flux and control flux, flux density located at upper air-gap is reduced while flux density at lower air-gap is enhanced. Consequently, levitation force in y negative-direction is generated and enable rotor to move toward center position. Therefore, this levitation force can be controlled by regulating value and direction of current in control winding.

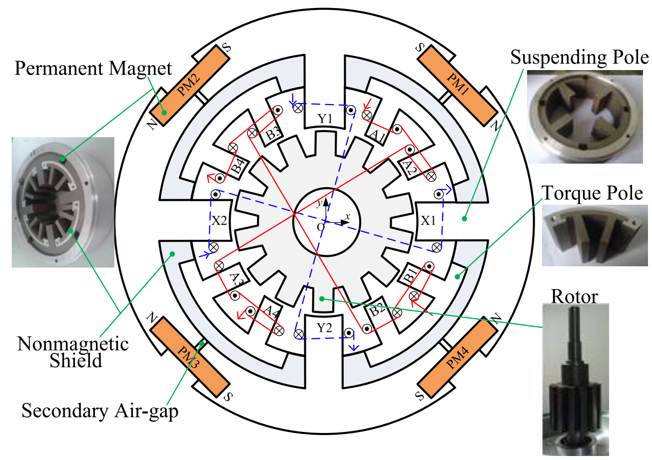

Fig. 2. Improved modular bearingless SRM.

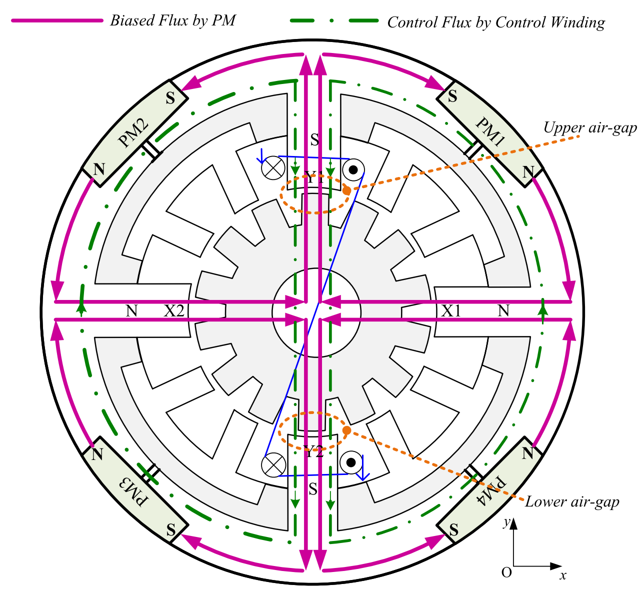

Fig. 3. Operating principle of proposed bearingless SRM.

2.3. Natural decoupling between torque and levitation force

Due to high speed application for bearingless motor, simple control algorithm is good for realizing the steady operation. Therefore, it is necessary to implement decoupling between torque control and suspending force control. It means that there is no or weak mutual effect between torque control and suspending force control. As shown in Fig. 4, torque pole is separated from suspending pole on the stator. For toque pole, when current flows through the windings of poles, torque