Direct control of torque and levitation force for dual-winding bearingless switched reluctance motor

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A R T I C L E   I N F O

Article history:
Received 25 July 2016
Received in revised form 16 December 2016
Accepted 9 January 2017

Keywords:
Dual-winding bearingless switched reluctance motor
Direct torque control
Direct force control
Torque ripple
Control strategy
Current control algorithm

A B S T R A C T

In dual-winding bearingless switched reluctance motors (BSRMs), an additional winding is placed on the stator poles in conventional switched reluctance motors (SRMs), which is mainly to achieve the function of levitation. Due to the hysteresis current control in existing control strategies for dual-winding BSRMs, the complicated derivation of winding-current expression was necessary, and some constraints were also introduced that increased the difficulties in designing the current control algorithm. In order to solve these problems, the direct control concept of torque and levitation forces is proposed and developed in this paper, named as direct torque control (DTC) and direct force control (DFC). Moreover, the torque ripple can also be reduced greatly. Firstly, the space voltage vectors of dual-winding BSRMs are defined for the main and levitation windings, respectively. After that, the rules and procedures for selecting the space voltage vectors are demonstrated in detail, and the system control block is also presented to facilitate the implementation of proposed control strategy. Finally, experimental results are provided to demonstrate the performance.

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1. Introduction

In conventional switched reluctance motors (SRMs), phase windings are mounted on the stator poles and no permanent magnets or windings on the rotor. The phase windings are energised separately by the asymmetric-half-bridge type converter. Therefore, SRMs own great advantages on the simple control strategy, fault-tolerant control, high speed capability, etc. [1–5]. In order to inherit the advantages of conventional SRMs, the bearingless motor technology was integrated with SRMs, and a reluctance-type bearingless motor was created, named as bearingless switched reluctance motors (BSRMs) [6–15].

The magnetic pulls are produced between stator and rotor poles when the phase winding is energised. The produced magnetic pull can be divided into tangential and radial components. In conventional SRMs, the radial components on each rotor poles are counteracted whereas the tangential components drive motor rotating at the expected speed. In BSRMs, the flux linkages flowing in the stator poles of the same phase are distributed asymmetrically, thus the radial components on the rotor are no longer counteracted and the radial force is produced on the rotor accordingly. With the active control of radial forces, the rotor shaft can be levitated when the bearingless motor is rotating at a high speed, which avoids the mechanical wear between the shaft and the mechanical bearing. Therefore, for the mechanical bearing, not only the lubrication system can be removed but also the problems of the maintenance and renewal can be solved, especially in some high-speed drive applications and in harsh environments with radiation and poisonous substances [6].

In the BSRM, according to the number of windings mounted on each stator pole, it can be divided into single-winding and dual-winding BSRMs. The dual-winding BSRM was firstly implemented by A. Chiba et al. in the 1990s [7]. The operation principle and control strategies were deeply investigated to implement the rotation and levitation experimentally for BSRMs [8,9,16–20]. After that, the single-winding BSRM was proposed and developed to obtain the same winding configuration on each stator pole as that in conventional SRMs [10–12]. The difference is that the coil on each stator pole is energised separately in single-winding BSRMs, whereas the coils in the same phase are connected in series or in parallel in conventional SRMs. In the single-winding BSRM, the winding current is controlled to provide not only the torque but also the levitation force, thus the design of control strategy is difficult and the control performance on the torque and levitation interacts with each
other. Therefore, some different pole-pair structures for BSRMs were proposed and investigated to simplify the control of torque and levitation forces [13–15,21–23].

In summary, the present work for BSRMs mainly focuses on the levitation mechanism, control strategies and novel structures protect [8,9,11–13,18–20]. On the basis of 12/8 dual-winding BSRMs, this paper studies the control strategy to simplify the control of torque and levitation force compared with existing control algorithms. The existing algorithm is to directly regulate the winding currents through the hysteresis current control to produce required torque and levitation forces. Therefore, the expressions of torque and levitation forces referring to winding currents were always derived to design relevant current control algorithm. As a result, the winding currents should be derived reversely and were expressed by the torque and levitation forces. Furthermore, some constraints were introduced to facilitate the solution of equations, which also increased difficulties on designing the current control algorithm more or less [8,12,20].

This paper proposes a different control concept of torque and levitation forces for dual-winding BSRMs. The current hysteresis control is removed from the power controller, and is replaced by the hysteresis control of torque and levitation forces. Therefore, the complicated current control algorithm is then not needed yet, and the constraints for the solution can be avoided as well. Moreover, not only the radial displacements but also the levitation forces are under the closed-loop control, which was not achieved in hysteresis current control methods for dual-winding BSRMs. In addition, because the direct torque control is implemented, the torque ripple can be greatly reduced.

The rest of paper is organised as follows. The operation principle of dual-winding BSRMs are demonstrated in Section 2. In order to facilitate the understanding of the DTC concept for SRMs, the principle of DTC for conventional SRMs is illustrated in Section 3. In Section 4, the space voltage vectors for main and levitation windings are defined according to the control of torque and levitation forces, respectively. After that, the rules and procedure for selecting the space voltage vectors are developed accordingly. Experimental results are presented to verify the proposed control method in Section 5 with conclusions made in Section 6.

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**Nomenclature**

- $\Psi$: flux linkage
- $\Psi_\alpha, \Psi_\beta$: flux-linkage vector components in the axes of $\alpha$ and $\beta$, respectively
- $\mu_0$: permeability of vacuum
- $\theta$: rotor angular position
- $c$: constant 1.49
- $F_\alpha, F_\beta$: radial forces on the direction of $\alpha$-axis and $\beta$-axis, respectively
- $h$: lamination length of the iron core
- $l_{ma}$: main-winding current of phase A
- $l_{a1}, l_{a2}$: levitation-winding currents of phase A at the direction of $\alpha$- and $\beta$-axes, respectively
- $l_0$: air-gap length between the stator and rotor poles
- $L_{a1}, L_{a2}$: $\alpha$-axis levitation-winding inductances of phases A, B and C, respectively
- $N_m, N_b$: winding turns of main winding and levitation winding, respectively
- $r$: radius of rotor
- $T, T_i$: instantaneous torque and instantaneous torque of phase A, respectively

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**Fig. 1.** Configuration of the studied dual-winding BSRMs: (a) Definition of positive winding currents. (b) Coil connections taking phase A as an example.

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**2. Operation principle of dual-winding BSRM**

**2.1. Levitation principle**

In 12/8 dual-winding BSRMs, there are three phases and two sets of windings mounted on each stator pole, i.e. the main winding and the levitation winding, as shown in Fig. 1(a). Taking phase A as an example in Fig. 1(b), the four coils mounted on four phase-A poles are connected in series to form phase-A main winding. The two coils mounted on the two poles at the direction of $\alpha$-axis, are connected in series to form $\alpha$-axis levitation winding of phase A. Similarly, the other two coils form $\beta$-axis levitation winding of phase A. The main winding conducts unipolar current to generate main magnetic flux, and the levitation winding conducts bipolar current to generate bias magnetic flux. When $\alpha$-axis levitation winding conducts current as illustrated in Fig. 1(b), the magnetic density of air gap 1 is enhanced whereas that of air gap 3 is weakened. Therefore, a radial force on the rotor is produced at the positive direction of $\alpha$-axis. Similarly, a positive radial force can also be produced along $\beta$-axis. Through regulating the winding currents reasonably, the levitation force at arbitrary direction can be provided to satisfy the requirement of levitation. Therefore, the continuous levitation forces can be secured via the alternate conduction of three phases.

**2.2. Mathematical model of torque and levitation force**

In dual-winding BSRMs, the torque and levitation force are relevant to motor mechanical parameters, the rotor angle position and the two winding currents. In order to obtain the expected torque and levitation force, the winding currents should be regulated reasonably according to different rotor angle positions. In hysteresis
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