A single-winding BSRMWR direct instantaneous torque control and direct levitation force control method

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Abstract. The stator and rotor of the bearingless switched reluctance motor are both double salient pole structures, when the traditional current chopping control method is used, the torque and levitation force of the motor will have large fluctuations. To solve this problem, this paper studies a direct instantaneous torque control and direct levitation force control (DITC&DFC) method suitable for single-winding bearingless switched reluctance motors. This method takes the instantaneous torque and the instantaneous levitation force of the motor as the directly controlled object, eliminates the current loop, and simplifies the control algorithm while suppressing the fluctuation of the motor torque and levitation force. A 12/8-pole single-winding bearingless switched reluctance motor with wide rotor teeth drive system is constructed, the Matlab/Simulink system simulation verifies the effectiveness and feasibility of the method.

1. Introduction
The bearingless switched reluctance motor (BSRM) utilize the similarity between motor structure and magnetic bearing, install the winding that generates levitation force on the motor stator, so that the motor along with the levitation and rotation function, which makes BSRM have a simple structure, no wear, good high speed adaptability and other advantages, in recent years received extensive attention [1-4].

Although BSRM is a special structure of SRM, its double salient structure and the way of power pulsed power supply haven’t changed, which makes the torque and levitation force of the motor fluctuate greatly during the commutation. In order to solve the problem of torque ripple in switched reluctance motors, scholars have conducted a series of studies[5-7]: Reference [5] uses an independent control strategy to optimize the current waveform of the BSRM with multiple objectives, which reduces the torque and levitation force fluctuations of the motor; Reference [6] proposed a second-order sliding mode-direct torque and direct levitation force control to solve single-winding BSRM torque and levitation force pulsation. Reference [7] applied a three-phase bridge converter to a switched reluctance motor, and compared the torque performance of asymmetric half-bridge and three-phase bridge converters through finite element simulation, the torque ripple of the motor is reduced by changing the winding structure.

This paper proposes a direct instantaneous torque control and direct levitation force control (DITC&DFC) method, the specific principle of DITC&DFC control method is analyzed, and takes the 12/8 pole single-winding bearingless switched reluctance motor with wide rotor teeth (BSRMWWR) as an example, through Matlab/Simulink system simulation, the torque and levitation force characteristics of the motor are compared when using the traditional current chopping control (CCC)
method and the DITC&DFC method, and the effectiveness and feasibility of the proposed method are verified.

2. Characteristics of BSRMWR

2.1. Decoupling principle

Figure 1 shows a schematic structural diagram of 12/8-pole single-winding BSRMWR. The mechanical angle of the rotor pole arc is 30°, and the mechanical angle of the stator pole arc is 15°. The four coils of each phase winding are spaced apart by 90°, and the magnetic flux of the motor is distributed in NSNS.

Figure 1. Structure of BSRMWR.

The inductance curve of the motor is shown in Figure 2. Define the alignment position of the centerline of the stator and rotor teeth as 0°. Due to the large mechanical angle of the rotor pole arc, the inductance forms a certain flat top area at the aligned position of the stator and rotor, passing equal currents in the inductance change area generates symmetrical excitation to generate torque, the inductance flat-top area is fed with currents of different sizes to form asymmetric excitation to generate levitation force, at this time, the coil don’t produce torque, so as to realize the natural decoupling of torque and levitation force.

Figure 2. Inductance curve.

In order to ensure the stable rotation and levitation of the motor, the 12/8-pole BSRMWR requires two phase winding to be turned on at the same time to work normally. Take phase A as an example. When the rotor position of phase A is at (-22.5°, -7.5°), the inductance of phase A winding is in the rising zone, at this time, the inductance of phase B winding is at (-7.5°, 7.5°), which is a flat top area,
so energizing phase A winding can provide torque for the motor, and energizing phase B winding can provide the motor with levitation force.

2.2. Traditional current chopping control method

The traditional current chopping control method (CCC) takes the average torque and instantaneous levitation force of the motor as the controlled object, for the given average torque and instantaneous levitation force, the given current values of the torque phase and the levitation phase are calculated through the mathematical model, and by controlling the power converter to control the current within a certain hysteresis range [8]. The working mode of the asymmetric half bridge is shown in Figure 3.

![Asymmetric half bridge operating mode](image)

Although the current chopping control can control the current within the hysteresis range, however, due to the non-linear relationship between BSRM torque and current, it cannot effectively limit large changes in torque. When the winding current is turned off, the large inductance value of the flat top area will cause a certain current tailing phenomenon, which makes the torque and levitation force of the motor fluctuate greatly, and affects the stable operation of the motor.

3. DITC&DFC method

3.1. DITC&DFC working principle

It can be seen from the operating principle of the motor that when the inductance curve is in the rising zone, the four stator windings of the phase can be supplied with equal currents to form a symmetrical excitation to provide the motor with the required torque. Figure 4 shows the working principle of DITC hysteresis.

![Torque hysteresis principle](image)

In Figure 4, the torque difference $\Delta T$ is the difference between the given torque $T_{\text{ref}}$ and the instantaneous torque $T$ of the motor, when $\Delta T$ is bigger than the internal positive hysteresis $T_{\text{min}}$ in the hysteresis controller, it indicates that the output torque of the motor is insufficient, the switching state of a given power converter set to positive state, in this state, the winding current will increase and the output torque of the motor will increase. When the torque difference $\Delta T$ is less than the internal negative hysteresis $T_{\text{min}}$, it indicates that the output torque of the motor is controlled within the hysteresis range, the switching state of a given power converter set to zero state, in this state, the winding current will enter freewheeling, and the output torque of the motor will slowly decrease. And when the torque difference $\Delta T$ is less than the external negative hysteresis $T_{\text{max}}$, it indicates that the output torque of the motor is relatively large, the switching state of a given power converter set to
negative state, in this state, a negative voltage is applied to the windings, and the output torque of the motor decreases rapidly.

When the inductance curve is in the flat top area, just make sure that the four windings of the floating phase are in different switching states, this can make the currents generated by the four stator windings of the phase not equal, thereby forming the asymmetric excitation to generate the levitation force required by the motor. Take phase A as an example to illustrate the DFC principle: when the levitation force $F_X$ in the $X$ direction is required to be greater than 0, it should be ensured that the current of the A1 winding is greater than the current of the A3 winding at this time, from the working principle of asymmetrical half bridge, the levitation force can be generated when the switching states of the A1 winding and A3 winding are as follows: $(+1,0), (0,-1), (+1,-1)$. The levitation phase winding current will show an upward trend overall under the combination of $(+1, 0)$, after the levitation phase is over, it will cause a large current tail to produce negative torque and affect the performance of the motor; The $(0, -1)$ can’t be continuously generated since the winding combination can’t ensure the motor current is continuously generated levitation force; The $(+1,-1)$ can continue to produce levitation force, and there is no serious phenomenon of current tailing. Therefore, DFC hysteresis control selects $(+1, -1)$ switch combination. When the force in the negative $X$ direction is to be generated, only need to change the switching states of the A1 and A3 windings. Similarly, the switching states of the A2 and A4 windings that generate the $Y$ direction levitation force $F_Y$ can be selected in the same way.

3.2. Control block diagram

Figure 5 shows the DITC&DFC block diagram based on an asymmetric half bridge power converter. First, the rotor position signal is detected by the photoelectric sensor installed inside the motor, determine the specific working interval of the phase by the detected rotor signal, when it is torque phase, using DITC method: convert the rotor position signal to the actual speed signal of the motor $n$, after comparing with the given speed $n^*$, the given torque $T^*$ of the motor is obtained by the PI controller, obtain winding current in real time through current sensor, the real-time torque value $T$ of the motor is obtained through the motor torque characteristic model, send the given torque and actual torque to DITC to get the switching signal of the power converter.

When it is levitation phase, using DFC method: the real-time displacement $x$ and $y$ of the motor shaft in the $X$ and $Y$ directions collected by the displacement sensor, after making a difference with the given positioning displacement $x^*$ and $y^*$, the given levitation force $F_X^*$ and $F_Y^*$ of the motor in the $X$ and $Y$ directions are obtained by the PID controller, compare the given levitation force with the real-time levitation force calculated by the winding current to DFC, get the switching state of the power converter.

![Figure 5. Control block diagram.](image-url)
4. Simulation analysis
To verify the effectiveness and feasibility of the proposed control method, using Matlab/Simulink simulation software to build a simulation model based on 12/8 pole single-winding BSRMWR system, and the motor parameters are shown in Table 1, the CCC and DITC&DFC methods are used for the motors respectively, and the torque and levitation force characteristics of the two control methods are compared and analyzed.

| Parameter                  | Value |
|----------------------------|-------|
| Stator yoke depth/mm       | 6.1   |
| Rotor yoke depth/mm        | 7.65  |
| Stator tooth height/mm     | 16.5  |
| Rotor tooth height/mm      | 7     |
| Air gap length/mm          | 0.25  |
| Stator pole radians/°      | 15    |
| Shaft diameter /mm         | 20    |
| Lamination length/mm       | 55    |
| Number of winding turns    | 30    |

The simulation conditions are as follows, the bus voltage is 75V, the motor's given speed is 2000r/min, and the given values of the levitation force in the X and Y directions are 30N and 50N, the torque reference value is 0.4 N•m, the inner and outer hysteresis widths of the torque are 0.01N•m and 0.03N•m, the levitation force hysteresis width is 2N.

Figure 6 shows the torque and levitation force waveforms of the motor under the CCC method. It can be seen from the figure that the torque pulsation of the motor under the traditional control method is relatively large, and the levitation force will have a large upper peak due to the current tail phenomenon during the commutation period.

![Torque and Levitation Force Waveform](image)

Figure 7 shows the torque and levitation force waveforms of the motor under the DITC&DFC method. Under the DITC&DFC method, the motor torque and levitation force pulsation is significantly reduced, torque and levitation force can track the given value better.
5. Conclusion

This paper proposes a DITC&DFC method, the specific working principle is analyzed and the control block diagram is given. This control method takes the instantaneous torque and instantaneous levitation force of the motor as the directly controlled object, it can effectively solve the problem of large fluctuations in motor torque and levitation force under traditional current chopping control methods. The effectiveness of the control method is verified by simulation.

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