Research Status of High-speed Permanent Magnet Motor Control System

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Abstract: In this paper, for the topology optimization design problem of low rotating iron consumption and high rotor strength high-speed permanent magnet motor and the high dynamic, high force-to-energy ratio and strong robust control problem of high-speed permanent magnet motor, we briefly introduce the research status of scholars at home and abroad on the two problems in order to realize the high-speed permanent magnet motor with low rotating iron consumption, high rotor strength, and fast dynamic response and to provide the basic conditions for further research.

Keywords: High-speed permanent magnet motor; Topology; Modeling; Control.

1. Research on the Topology of a Permanent Magnet Motor with Low Rotating Iron Consumption and High Rotor Strength

High-speed permanent magnet synchronous motors, brushless DC motors, and switched reluctance motors are new types of high-speed brushless motor drive systems that have appeared in recent years, among which the double-convex pole reluctance motor, represented by the switched reluctance motor, has the tendency to replace the traditional speed control motor with its superior performance and incomparable advantages. The common features of biconvex reluctance motors are: simple motor structure, neither permanent magnet nor winding on the rotor, easy to dissipate heat and cooling, solving the problem of permanent magnet demagnetization caused by centrifugal force and vibration and poor heat dissipation due to the permanent magnet and winding on the rotor, with the advantage of high-speed operation, adapting to a variety of harsher working environments, and the light weight of the motor rotor, enhancing the fast response and speed of the system. The light weight of the motor rotor enhances the fast response and robustness of the system. However, a thing cannot be perfect; a switched reluctance motor has some aspects of the same shortcomings, such as torque pulsation, its inherent vibration and noise problems, low utilization of the motor winding, complex power inverter topology, large size, complex control strategies, and so on. Therefore, experts and scholars from all over the world have never stopped exploring and researching various new topologies of biconvex reluctance motors.

Since the 1990s, some new types of biconvex reluctance motors have been continuously proposed and studied. Each of these motors has its own characteristics, performance advantages, and application occasions, which largely enriches the connotation of the drive speed regulation field. The stator permanent magnet-type motors represented by the new double-bump permanent magnet motor [1] and the flux-switching permanent magnet motor [2-4] have attracted extensive attention and research from scholars in the domestic and foreign motor communities. These two new types of permanent magnet brushless motors have common points in structure, such as the stator and rotor being both convex pole structures; the stator is centrally wound; the permanent magnets are embedded in the stator yoke; and there are neither permanent magnets nor windings on the rotor. However, there is a big difference in the operation principle: a double-convex pole permanent magnet motor is essentially a brushless DC motor, and its opposite potential waveform is close to a square wave. The flux-switching permanent magnet motor is essentially a permanent magnet synchronous motor, i.e., each phase of the permanent magnet magnetic chain and the inverse potential waveform are close to a sinusoidal waveform. The current research results show that both motors have the advantages of high power density and high efficiency.

In 1992, the American scholar T.A. Lipo first proposed the Double Salient Permanent Magnet Motor (DSPM), using permanent magnets to replace the auxiliary excitation windings, which obviously increases the power density and material utilization of the motor. The existence of permanent magnets reduces the inductance of the windings, improves the phase change of the windings, and has a higher efficiency. In addition, in-depth research has been carried out on various 6/4-pole or 4/6-pole permanent magnet biconvex pole motors. Southeast University, Huazhong University of Science and Technology, Nanjing University of Aeronautics and Astronautics, and Shanghai University have carried out in-depth and innovative research on biconvex permanent magnet motors with various topologies. Literature [1] has carried out comprehensive and in-depth research on the motor ontology design and control mode of DSPM, etc. The group led by Prof. Cheng Ming of Southeast University proposes a new type of DSPM with whole-pitch winding on the basis of existing DSPMs, which have the armature windings placed in one stator slot apart, no winding is placed in the stator slot directly opposite to the permanent magnet, and the number of turns of the windings is reduced by half of the original one, which reduces copper. In DSPM, the reluctance torque generated by the change in winding self-inductance is no longer the main electromagnetic torque but only a disturbing factor causing torque fluctuation, and the torque generated by the interaction between the permanent magnet and the winding current becomes the main electromagnetic torque. The permanent magnet induces a bi-directional alternating electromotive force in the winding, and the working current of the winding is a bi-directional alternating current, and the mutual inductance of the winding is significantly increased, which is a good solution for the motor. The mutual inductance between the windings increases significantly, making it difficult to analyze and control.

In 1997, French scholar E. Hoang proposed a new type of double-convex-pole flux-switching permanent magnet motor (FSPM) with permanent magnets placed in the stator, the stator of which is made of U-type silicon steel core and permanent magnets assembled sequentially, and there are no windings or permanent magnets on the rotor. FSPM is essentially a permanent magnet synchronous motor, but compared with the traditional rotor-type permanent magnet synchronous motor, FSPM has significant incomparable advantages: Its rotor is a simple convex pole structure without any form of windings or permanent magnets, which is suitable for high-speed operation and easy to dissipate heat and cooling. The motor's no-load magnetic chain shows a change in bipolarity, which increases the motor's power density and material utilization; the aggregation effect of the U-type iron core makes the no-load air-gap magnetic field can be designed to be very large, thus further increasing the power density of the motor and reducing the size of the motor; The special structure makes the permanent magnet magnetic circuit and the armature magnetic circuit connected in parallel, which is convenient for weak magnetism control. Due to the complementary nature of the armature windings, the high harmonic components in the permanent magnet magnetic chain and the inverse electromotive force waveforms are reduced, so that compared with the ordinary permanent magnet synchronous motors, a high sinusoidity can be obtained under the condition of adopting the straight groove of the rotor [2-4].

The structure and operation principle of the above double-convex pole permanent magnet motors are different, each with its own advantages and scope of application, but they all have heteropolar type motors with large rotating iron consumption for high-speed operation.

The prototype of the homopolar type motor is the unipolar DC excitation generator, also called Faraday generator, which is divided into two types according to the rotor structure: disc type and cylindrical type, in which the stator and rotor of the cylindrical rotor homopolar type are both convex pole structures, the rotor is a solid rotor structure with neither excitation winding nor armature winding, and the stator consists of two parts independent of each other: the stator with armature winding and the stator with excitation winding. In the research of homopolar AC motor topology, Active Power Company in the U.S. proposed a solid rotor homopolar solid rotor electro-excitation motor/generator topology and applied it to its high-power energy storage flywheel, as shown in Fig. 1.

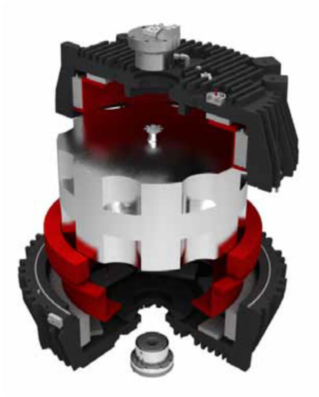

Figure 1. Co-pole type solid rotor electrically excited motor/generator of Active Power, USA

H. M. Cheshmehbeigi and E. Afjei have analyzed, simulated and experimentally investigated the brushless DC motor with electro-excited homopolar convex pole topology [6] as shown in Fig. 2.

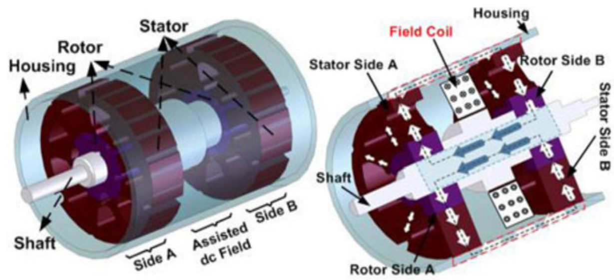

Figure 2. Topology of homopolar electrically excited brushless DC motor

Literature [7] designed a 10 hp homopolar type motor with high temperature superconducting coils for both excitation and armature windings as shown in Fig. 3.

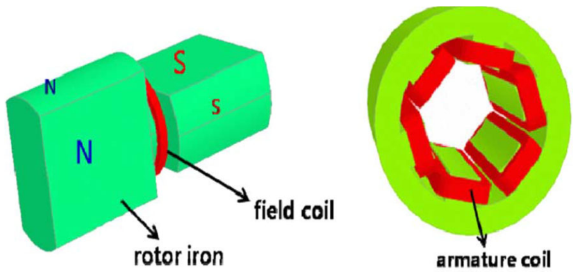

Figure 3. High-temperature superconducting homopolar motor topology

The main advantage of the homopolar motor as a high-speed motor is that its excitation magnetic field has no magnetic pole alternation but only amplitude change when passing through the axial closed circuit formed by the rotor, which can effectively reduce the rotating iron consumption. The current research on the topology of homopolar motors mainly focuses on the electro-excited homopolar convex-pole brushless DC motors and electro-excited homopolar asynchronous generators.

2. Nonlinear Dynamic Modeling, Decoupling and Control of Double Convex Pole Permanent Magnet Motor

The homopolar solid rotor permanent magnet motor is essentially a double-convex pole permanent magnet motor. The current research on the double-convex pole motor mainly focuses on the linear analysis method of static characteristics. It is shown that the double-convex pole motor because of its stator and rotor poles are convex pole structure, there is a significant edge effect and a high degree of local saturation phenomenon, so the motor air gap magnetic field spatial distribution is very complex, with the rotation of the rotor motor in the magnetic field distribution should also be made for the cyclic changes in the winding inductance and the magnetic chain is the rotor position angle and the current of each winding of the nonlinear function. Neglecting the effect of magnetic circuit saturation, assuming that the inductance does not change with the current under the premise of the establishment of a linear model, but the model corresponds only to a specific operating point, when the load or speed changes, corresponding to a set of approximate transfer function model, is not applicable to the analysis of the entire operating range. In the control of motors, many control strategies require accurate mathematical models, so the linear model can no longer meet the needs of high control performance.

The nonlinear model accurately considers the motor core magnetoresistance and saturation effect, which is closer to the actual situation, and the key is to find the nonlinear mapping relationship of the magnetic chain. The stator and rotor of homopolar solid-rotor double-convex-pole permanent-magnet motor are both convex poles, the inductance and magnetic-chain characteristics are strongly nonlinear, and the equivalent circuit and magnetic circuit show strong switching and coupling, which makes it difficult for conventional linear or quasi-linear models to accurately reflect the actual characteristics of the object to be controlled. Accurate motor models are important for improving motor operation efficiency, optimizing speed regulation performance, eliminating torque pulsation and realizing position sensor-less control. The core of the modeling of biconvex permanent magnet motor is to accurately describe the mapping relationship between magnetic chain, current and rotor position. Since it is difficult to obtain such a theoretically accurate binary function, the modeling scheme usually consists of using some mathematical method to reconstruct the complete and continuous nonlinear mapping of the magnetic chain to current and rotor position after obtaining a finite number of discrete magnetic chain data. In terms of nonlinear system modeling, literature [8] proposed a nonlinear modeling and identification method for constructing explicit Volterra filters in the defining domain of the short-time Fourier transform domain. Literature [9] performs model identification of nonlinear systems based on generalized global least squares and equational constraint methods. Literature [10] uses the edge optimization method to discuss the optimization problem of a finite dimensional system on a bounded set, and obtains a convergent sequence of parameter optimization through iterative approximation to realize the full model parameter identification of the stator magnetic chain, stator resistance, mutual inductance, moment of inertia, and other parameters of the electric machine, which has a faster convergence speed compared with the stochastic search algorithms and particle filtering optimization methods, and has certain advantages in terms of real-time performance and identification accuracy. It has certain advantages in terms of real-time and recognition accuracy.

The nonlinear model established by using mechanism analysis and system identification methods, there is a strong dynamic coupling between the motor speed and the stator magnetic chain, and decoupling control is one of the important methods for realizing high-performance motor control, such as magnetic field oriented control, direct torque control, differential geometric state feedback control, linear decoupling control of the inverse system, and internal mode control, etc. The magnetic field oriented control realizes a steady state approximate decoupling relationship between the speed and the magnetic chain only when the magnetic chain reaches steady state and remains stable. Magnetic field orientation control is a steady state approximate decoupling, only when the magnetic chain reaches the steady state and remains stable, the speed and the magnetic chain to meet the decoupling relationship; direct torque control is the use of torque and magnetic chain hysteresis loop to achieve dynamic decoupling; differential geometry method can realize the dynamic decoupling of the system, but it needs to be transformed into a geometric domain to discuss, and the mathematical tools are complex and abstract, not easy to master; inverse system method is a linearized decoupling control, with physical concepts, linear decoupling control, internal mode control, etc.. decoupling control, with the advantages of clear and intuitive physical concepts, simple and straightforward mathematical analysis, has been applied in multivariable decoupling control, internal mode control, but there are shortcomings such as the robustness and adaptability of the motor parameter changes are not ideal, and the resistance to load perturbation is not strong, etc. [41], the combination of which with the neural network can effectively improve the robustness and adaptive capacity of the inverse system method, and the neural network inverse system is used to replace the analytical inverse system. Combining the nonlinear approximation ability of neural network and the fault tolerance and robustness of its distributed structure with the linearized decoupling characteristics of the inverse system, the motor is dynamically decoupled into a linear rotational speed sub-system and a linear stator magnetic chain sub-system, and the neural network inverse system is constructed to realize the linearized dynamic decoupling control of the motor, which can significantly improve the dynamic response speed of the system.

The high speed motor drive system not only needs fast response capability, but also should have good robustness in the case of motor parameter ingress or subject to internal and external perturbations. Literature [11] based on Lyapunov stability theorem design parameter ingestion, unmodeled dynamic estimation algorithm and robust sliding mode controller to eliminate the effects of real-time uncertainty, but also can effectively reduce the current ripple, the sliding mode control method and wavelet neural network fusion, the introduction of online wavelet neural network controller in the feedback channel and the sliding mode controller in parallel with the sliding mode controller to construct a robust wavelet neural network sliding mode controller, this method with the help of the robustness, wavelet neural network control, and the wavelet neural network controller, the sliding mode controller. This method realizes dynamic decoupling control and high-precision speed tracking performance with the help of the robustness of the sliding mode control, the online learning ability of the neural network and the recognition ability of the wavelet analysis. The integration of nonlinear control and intelligent control theory has made great progress in suppressing disturbances, improving dynamic performance and robustness, but the research on the stability and robustness analysis of nonlinear control systems for electric machines is relatively weak and far from being perfect.

3. Conclusion

In summary, according to the existing foreign literature, there is less research literature on the design theory and control method of homopolar type solid rotor permanent magnet motor, and there is still a gap in the domestic research on the topology and control strategy of homopolar type solid rotor permanent magnet motor. However, the literature related to the design and control of homopolar-type electro-excitation motor, the design and control of high-speed rotor permanent magnet-type motor, and the design and control method of biconvex-pole permanent magnet motor is of some significance and inspiration for the research of this project. Since the low rotating iron consumption and high-strength solid rotor structure of homopolar-type motors are particularly suitable for high-speed operation, it is necessary to explore and study the topology and control strategy of high-speed homopolar-type solid-rotor permanent magnet motors, so as to provide China's new-generation energy-saving high-speed power machinery with new ideas and methods for the study of a new type of high-speed permanent magnet motors with low rotating iron consumption and high rotor strength.

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References

[1] Wenxiang Zhao, K. T. Chau, Ming Cheng, etc. Remedial Brushless AC Operation of Fault- Tolerant Doubly Salient Permanent-Magnet Motor Drives[J]. IEEE Trans. Ind. Electron., 2010, 57(6): 2134-2141.

[2] Seyed Ehsan Abdollahi and Sadegh Vaez-Zadeh. Reducing Cogging Torque in Flux Switching Motors With Segmented Rotor[J]. IEEE Trans. Magn., 2013, 49(10): 5304-5309.

[3] Benjamin Gaussens, Emmanuel Hoang, Michel Lécrivain, etc. A Hybrid-Excited Flux- Switching Machine for High-Speed DC-Alternator Applications[J]. IEEE Trans. Ind. Electron., 2014, 61(6): 2976-2989.

[4] Chang-Chou Hwang, Chia-Ming Chang, San-Shan Hung, etc. Design of High Performance Flux Switching PM Machines with Concentrated Windings[J]. IEEE Trans. Magn., 2014, 50(1): 4002404.

[5] H. M. Cheshmehbeigi, E. Afjei. Design Optimization of a Homopolar Salient-Pole Brushless DC Machine: Analysis, Simulation, and Experimental Tests[J]. IEEE Trans. Energy Convers., 2013, 28(2): 289-297.

[6] Fengzheng Zhou, Jianxin Shen, Weizhong Fei, etc. Study of Retaining Sleeve and Conductive Shield and Their Influence on Rotor Loss in High-Speed PM BLDC Motors[J]. IEEE Trans. Magn., 2006, 42(10): 3398-3400.

[7] Ji-Kwang Lee, Sang Ho Park, Yungil Kim, etc. Electrical Properties Analysis and Test Result of Windings for a Fully Superconducting 10 HP Homopolar Motor[J]. IEEE Trans. Appl. Supercond., 2012, 22(3): 5201405.

[8] Yekutiel Avargel, Israel Cohen. Modeling and Identification of Nonlinear Systems in the Short-Time Fourier Transform Domain[J]. IEEE Trans. Signal Process., 2010, 58(1): 291- 298.

[9] Christoph Hametner and Stefan Jakubek. Nonlinear Identification with Local Model Networks Using GTLS Techniques and Equality Constraints[J]. IEEE Trans. Neural Netw., 2011, 22(9): 1406-1418.

[10] D.U. Campos-Delgado, E.R. Arce-Santana, D.R. Espinoza-Trejo. Edge optimisation for parameter identification of induction motors[J]. IET Electr. Power Appl., 2011, 5(8): 668-675.

[11] Zhiqiang Wang, Yan Zhao. Speed Mode Synergetic Control Approach for Magnetic Suspended Reaction Flywheel[J]. Applied Mathematics & Information Sciences, 2013, 1L, 107-112.