



A COMPARATIVE ANALYSIS ON CONTROLLERS OF BEARINGLESS SWITCHED RELUCTANCE MOTOR

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Abstract

A variable speed motor is a switched reluctance motor (SRM) most widely used in many number of applications in industries. The major challenge in switched reluctance motor is production of high noise and vibrations due to its double salient design. For this bearingless switched reluctance motor (BSRM) is a feasible solution. It is an electromagnetic device combining conventional motor with active magnetic bearing. Currently, in case of BSRM the research have been fastened due to its simple and rugged construction, cost and fault tolerance as compared to conventional motors. This paper gives a comparative analysis on BSRM components, its design considerations and different types of intelligent controllers are explained in detail.

Keywords: SRM, BSRM, AMB, Radial force

I. Introduction

In the recent years the trend in development of machinery for industries and machine tools is increasing much more to increase compactness and speed for increased outputs. Switched reluctance motors are gaining popularity because of its simple and rugged construction, cost and fault tolerance as compared to conventional motors such as DC and induction motors. SRMs have been extensively used in various applications in industries and house utilities such as mining drives, linear drives, etc. [XXVI]. Literature shows conventional SRM has suffering from the high acoustic noise and vibration due to its double salient structure. For this BSRM is a feasible solution. A comparative analysis on BSRM is carried out in this paper. A BSRM is a machine combining with electromotor with active magnetic bearing (AMB) [XVI]. The advantage of BSRM is there is no wear losses because no

mechanical contacts with rotor while rotation. The speed range of BSRM is 100-1000 rpm [X]. It can also operate in low temperature conditions. The existing literature says more accurate controls such as vibration control and direct torque control are need to be selected for BSRM. The intelligent controllers are promising future research for machine tools and other industries [XX].

The magnetic structured BSRM consist of rotor and stator. Many methods have been applied and used separate coils to produce the radial force and motoring action [XXVIII, XXXI]. As mentioned earlier SRM has limitations such as torque ripple, vibrations of stator and rotor and audible noise from aerodynamic and stator vibrations. These problems are produced by non-uniform airgap and electrical commutations. From the literatutre the said problems are overcome by the rotor magnetic materials in SRM. Table 1 shows the main problems that are associated with the SRM and some possible solutions [XXIV]. From the Table 1 it can be seen that BSRM is a feasible solution for all the existing problems associated with the SRM. Replacing the AMB in place of mechanical bearing offers more stabilized rotations in SRM.

Table 1: Solutions for main problems of SRM

Problem	Solution
Torque ripple	Forcing negative voltage for increased current drop rate, Optimizing commutation timing, Adaptive neuro-fuzzy compensating controller, Rotor tooth shapes
Vibration of rotor on rotational frequency (flexible rotor)	BSRM
Vibration of rotor (flexible bearings)	BSRM
Natural vibration of stator (flexible stator)	Stator construction, BSRM, Intelligent control of transistors in the inverter
Aerodynamic noise	Filling rotor slots, Low pole number, Long air gap, Attenuating the vibration of the rotor (BSRM)
Audible noise from vibrating stator	Stator construction, BSRM, Intelligent control of transistors in the Inverter

In this paper a comparative analysis has been carried out on BSRM. Section 2 presents the thoeoretical background of BSRM. Section 3 covers the design consideration of BSRM. Moreover, it describes the BSRM basic working principle. Section 4 reviews the intelligent controllers of BSRM. This section focuses on the speed control and direct torque control. Finally, section 5 concludes the paper.

II. Theoretical Background of BSRM

In order to get high speed a bearing is an important component in machinery tools. The wear loss due to friction is a problem of bearing. This problem can be overcome by the non-contact bearings such as magnetic, air, hydrodynamic types.

The problem of acoustic noise, friction and vibration can be eliminated by these type of non-contact bearings. Apart from these types, AMB is most reliable because it has high stiffness and load capacity e.t.c. A BSRM is a combination of motor function and AMB. The combination aim is to produce rotational force along with translational force. These two forces can be produced either by permanent magnets or coil sets. Based on the developing torque, there are three types of bearingless motors: Firstly, Permanent magnet type –the torque developed by the Lorentz force. The torque is controlled independently in this type. Secondly, Induction type –Low cost, easy design and higher radial force are the pros of this type. But complicated vector control is needed [XIX, XV].

The third is reluctance type bearingless motor – it is almost like to SRM. Due to non uniform magnetic reluctance and additional winding in the stator produces the motoring torque and radial suspension force simultaneously. There are several pros are identified incase of BSRM. First, there is no coils and magnets on the rotor, hence less cost. Second, in case of emergency it can be quickly broken. Third, it can also operate at low temperature condition. Fourth, rotational and translational forces increased with one each other [I, V]. In high speed and operation environment AMB is very optimal. In an AMB, a force exerts to the stator by the horseshoe magnet, which is expressed by [IX]

$$F = \frac{1}{4} \mu_0 N^2 A \frac{i^2}{l_g^2} \cos \alpha \quad (1)$$

where μ_0 is permeability of air, N and A are no. of rotations and cross sectional area of the coil, i is winding current, l_g is air gap length and α is the pole glancing angle.

III. Design Considerations of BSRM

Firstly in the year 1998 M.Takemoto was presented a paper on design characteristics of BSRM. The author concluded that radial force is a function of winding and motor currents and rotor position as well [XVII]. In the next paper of the same author is investigated that the average torque could be controlled by giving square wave currents to main winding of the motor [XXII]. Later in the past decade so many authors proposed different design methodologies. In [XV] a hybrid 12/14 pole BSRM was proposed. In that paper that the author proposed that, the separated poles design reduces the torque ripple.

A. Various pole Combinations

From the existing literature in the recent years the authors proposed various stator rotor pole combinations for efficient operation BSRM. In 2013, TeemuHalmeaho et al. [XXIII] investigated the feasibility study on 4/2 AMB switched reluctance motor. Fig.1. shows the test rig of BSRM.

In the literature Wang et al. [XXV] half stator pole approach was proposed. In this model the concluded that flux reversal resulting the higher stator core losses. In order to overcome the problem Xu et al. [XXX] proposed a hybrid 12/14 pole type BSRM with no flux reversal in stator is shown in Fig.2.

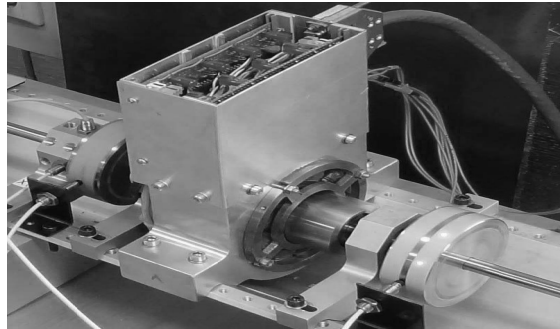


Fig. 1: The test rig of BSRM

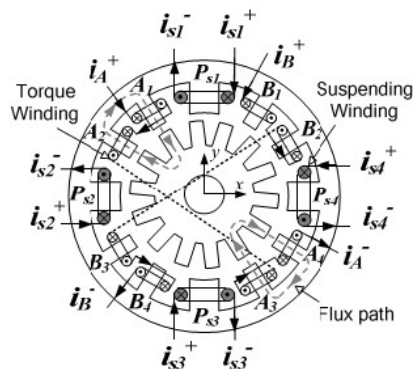


Fig. 2: Structure of 12/14 BSRM

Later in 2014, BingkunXue et al.[VI] investigated a novel 12/14 bearingless permanent biased switched reluctance motor. In this investigation the author found different conclusions. Firstly, while designing the permanent magnet need to set the width values before the height of the magnets. Secondly, the suspending arc has linear in nature with pole arc. The structure of 12/14 bearingless permanent biased switched reluctance motor shown in Fig. 3.

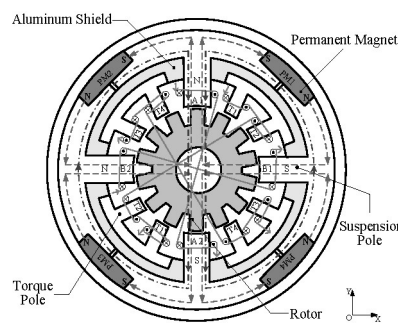


Fig. 3: Structure of 12/14 bearingless permanent biased switched reluctance motor

In [IV] Firdausaahmed et al. was developed a bridge configured wounded SRM using magnetic equivalent circuit method. To develop this system author used ANSOFT Maxwell 2D software. The author concluded that the model used to produce radial

force, that can either used to vibration control. Fig. 4.(a) & (b) shows the bridge configured for one phase and cross section of motor with phase – A coils.

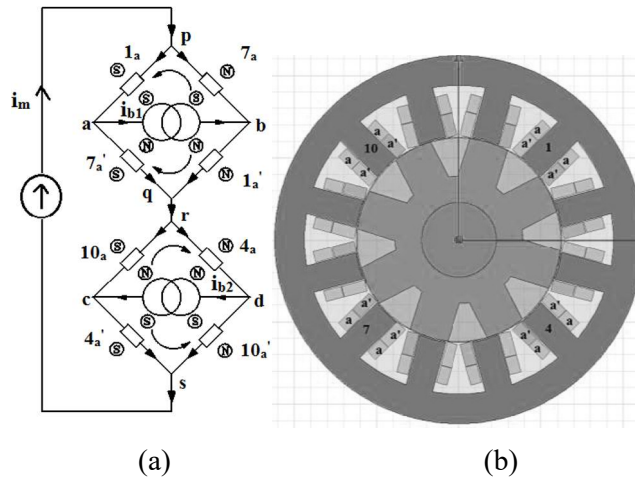


Fig. 4: (a) The bridge configured for one phase
(b) cross section of motor with phase – A coils

Zeyuan Liu et al.[XIV] explore the design of a novel 12/4 BSRM with decoupling operation principle. In this case study the author realized that with the proposed 12/4 wider rotor teeth design, the torque is improved than the conventional systems. The decoupling principle of 12/4 wider rotor teeth BSRM shown in Fig. 5.

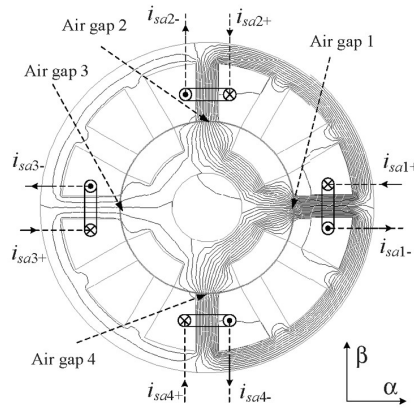


Fig. 5: 12/4 wider rotor teeth BSRM

So, from the existing literature it can be observed that with the use of 12/14 pole BSRM and different configurations the output is improved. More research yet to be done on BSRM pole combinations.

B. Phase Connections or Phases of BSRM

Since from 1999, so many authors investigated different winding connections for BSRM. In [XVIII] a new control method was proposed with one winding

connection. The finite element analysis (FEA) is used to produce the radial force in stator. The winding connection is shown in Fig. 6.

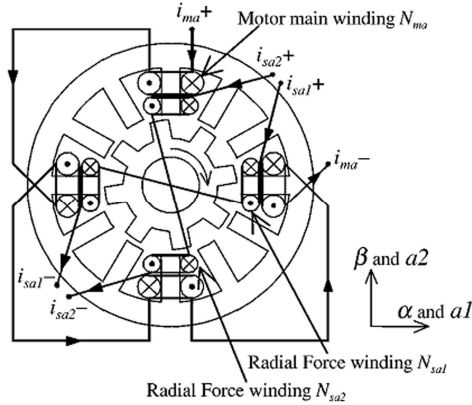


Fig. 6:Winding configuration of phase-A

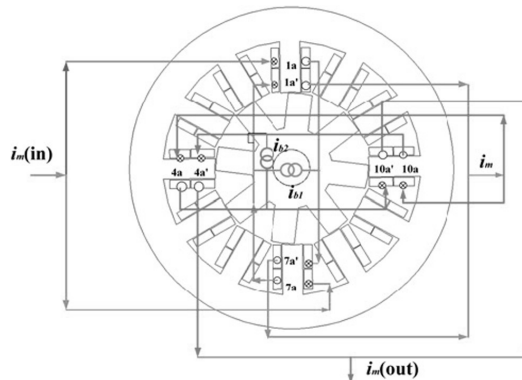


Fig. 7: The 12/8 BSRM bridge configured single phase connection

In the past decade so many configurations was proposed with different winding connections for radial force production in BSRM. W.K.S khoo et al. [XXVII] explored th multi-phase bridge configured BSRM. By using FEA the author found a cost saving solution and with the bridge configuration 10% less power loss than other set od windings. Later in [XII] Lee et al. implemented a hybrid BSRM with suspended stator poles named as brushless switched reluctance motor (BLSRM).The author found that with two types of windings in the same stator can minimise the magnetic coupling and it maintain the better mechanical stiffness.As mentioned earlier in [IV] that the author extended bridge configure set windings of 12/8 BSRM in the next continued papers [II, III]for generation of radial force using analytical method. In this extension paper the author investigated that without affecting output the produced radial force can be controlled by regulating the bridge currents.Fig. 7.shows the 12/8 bridge configured single phase connection.

IV. Control Method of BSRM

Literature says different authors proposed different control schemes to control the BSRM. The control of BSRM means controlling of force and

torque. Jianbo Sun et al. [XI] proposed the novel radial Force Control (FC) scheme and Direct Radial Force Control (DRFC) for non-linear BSRM. The proposed Artificial Neural Network (ANN) based control scheme is shown in Fig.8.

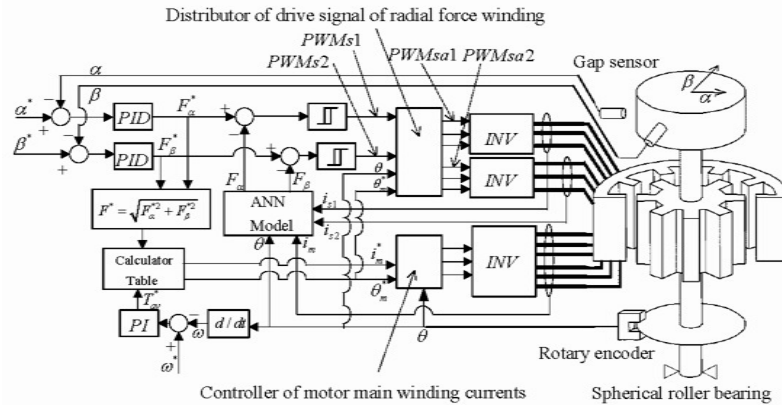


Fig.8: Artificial Neural Network (ANN) based control scheme for BSRM

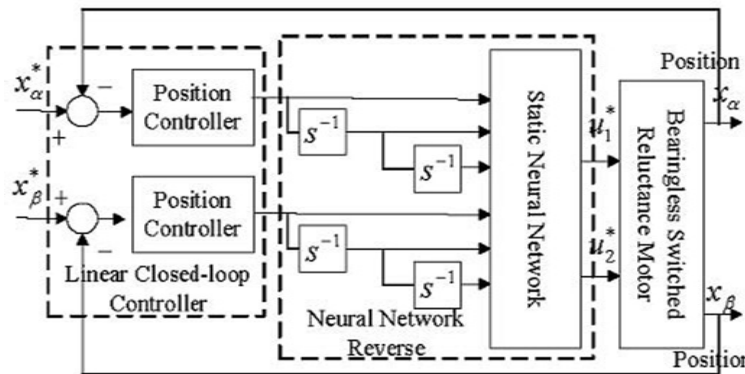


Fig. 9: Inverse decoupled neural network control scheme for BSRM

In [VIII] the author proposed neural network scheme for BSRM dynamic control. A neural network inverse scheme has been used to get extensive performance of BSRM. A static neural network is decoupling the BSRM and the integrators. Fig. 9. Illustrating the control structure of the proposed system.

An experiment was conducted by Yang et al. [XIII] on 12/8 pole BSRM. The author has taken effective considerations while doing an experiment like mutual inductance and balanced position of rotor in the airgap. The author concluded that production of radial force is same in all the conditions but the rotor position has changed according to speed. In 2012 Li Chen et al. [VII] proposed a new speed regulation technique for 8/6 single winding BSRM. Based on the existing literature the author proposed the single layer winding and concluded with experimental results proved that machine could operate well. The proposed structure shown in Fig. 10.

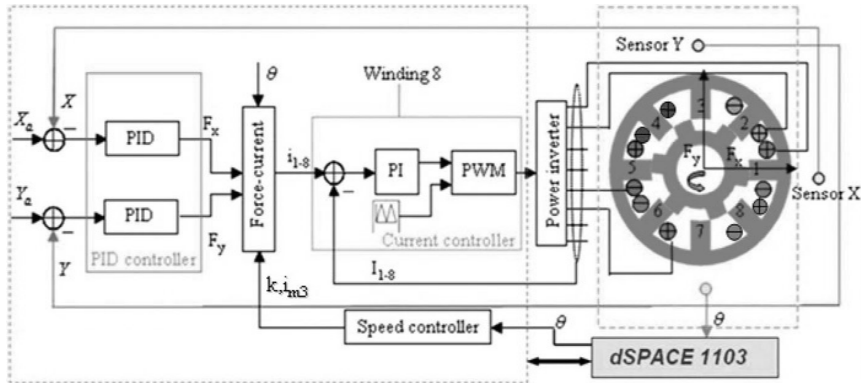


Fig. 10: Control structure of 8/6 single winding BSRM

In order to eliminate the ripples in radial force and torque and to reduce complexity of control system of BSRM, the combination of direct force control and direct torque control was proposed by Qin Sun et al [XXI]. The main aim of this control is to control the radial force and torque simultaneously. The proposed system was carried out by Matlab/Simulink. The author finally concluded that simplified control system fastened the dynamic response of the network. Simplified & proposed control system is shown in Fig. 11.

After the simplified control system of BSRM in [XXI], Xin Cao et al. [XXIX] proposed that same configuration with some novel changes. The novel control system was applied to single winding BSRM to minimize the ripples in torque and radial force. The author concludes with the experimental results that torque ripple is minimized by 80% and radial displacement by 29%. The proposed control scheme is shown in Fig. 12.

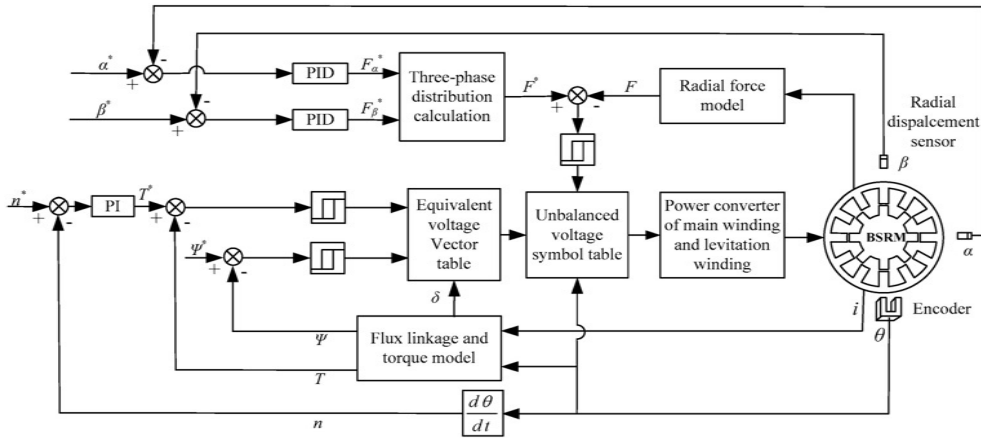


Fig. 11: Simplified control system of BSRM

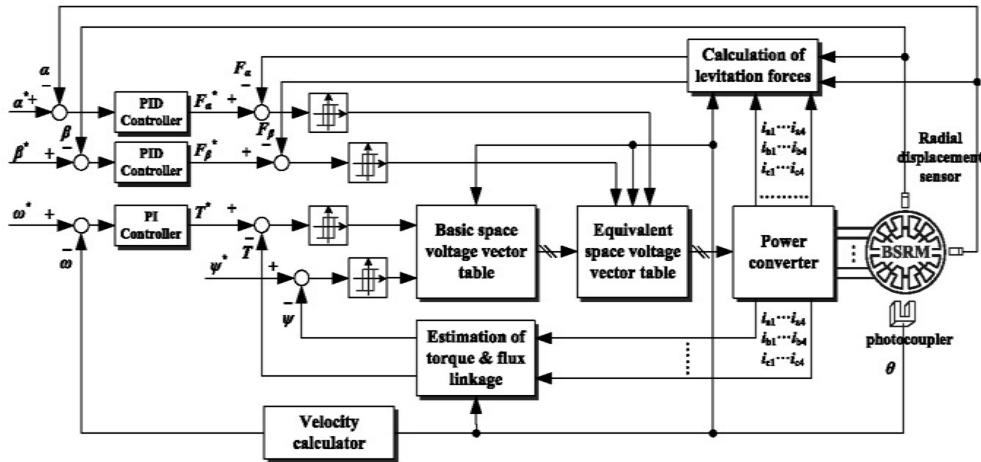


Fig. 12:The control structure for single winding BSRM

It has been observed that, so many authors have been investigated and proposed different models, approaches for production of radial force in BSRM. The combination of FC and DRFC are also proposed in different configurations.

V. Conclusion

The comparative analysis on BSRM has been performed in this manuscript is demonstrating that the winding connections and intelligent control schemes have more designing factors which are to be consider more in future to minimise the complexity of the system. The researchers need to concentrate on controllers and the advancements in the structure to reduce torque ripples much more in single winding BSRM. In this survey the technological challenges and schemes of the BSRM are discussed. There are two major advantages identified by the use of BSRM. Firstly, the design of BSRM is simple and rugged construction. Second, the torque ripple, acoustic noise and vibrations are eliminated with the use AMB. So that, the motor can be used at different environmental conditions. In these consequences many developments are ongoing in this area to improve overall efficiency of the motor.

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