# Unbalance Detection in Flexible Rotor Using Bridge Configured Winding Based Induction Motor

Natesan Sivaramakrishnan, Kumar Gaurav, Kalita Karuna, Rahman Mafidur
Department of Mechanical Engineering,
Indian Institute of Technology,
Guwahati, Assam -781039, India.
n.siva@iitg.ernet.in[1], gaurav.kr@iitg.ernet.in [2], Karuna.kalita@iitg.ernet.in [3] , mafidur@iitg.ernet.in [4].

***Abstract*—An eccentric rotor position produces unbalance in the field and generates a net radial force called unbalance magnetic pull (UMP). The magnitude and direction of this UMP mainly depends on the degree and type of the eccentricity. The electromechanical interaction in an induction machine is due to the coupling between magnetic fields and the eccentricity in the rotor motion and both radial and tangential electromagnetic forces are generated in the air gaps due to this interaction. This paper investigates a specialized winding scheme for a three-phase, four-pole induction machine called a bridge-configured winding (BCW) which can be used for generating a controllable transverse force and also can be used for monitoring the health of a machine. This paper addresses the latter one where unbalance can be detected in the system due to the currents generated in the bridges. These currents are called bridge currents. In this way the bridge current can be used as a measure of the unbalance present in the rotor. To develop the experimental setup the stator winding of a 37kW three phase four-pole induction machine was modified by incorporating a bridge-configured winding. Existing rotor of the motor has been replaced with a longer rotor and a perforated disc is inserted in the rotor to introduce different unbalance. Experiments were carried out to check the presence of bridge current which is an indication of an unbalance present in the system and it has been also shown that the bridge current changes with the unbalance present in the system.**

***Keywords—Induction machine; Bridge configured winding connection;***

## I. INTRODUCTION

Induction machines are the most common type of electrical machines used to drive high speed rotating machine. Vibration is a major concern for high speed rotating machines and unbalance present in the system is one of the most important reasons behind this. In an electrical machine unbalance present in the system generates eccentricity which leads to uneven flux distribution and then UMP. It has been realized that if the distribution of the additional flux is of a pole-pair ($p\pm1$, where, $p$ is the number of fundamental pole pairs) difference with respect to the torque-producing component of flux, significant net lateral force acting across the air gap can be produced. The presence of additional fields of one-pole pair difference from the main field is usually observed in the study of UMP. These fields arise because of rotor eccentricity and cause a distortion to the main field in the air gap. As a result the rotor tends to attract to the stator in the direction where flux density is highest. The use of this asymmetric magnetic field on force production has been utilized in self-bearing machines as well as in the active control of flexural rotor vibration in electrical machine. However, in these applications, the asymmetry in the field is deliberately imparted in the machine so as to produce controllable transverse force. This imparting of asymmetry is basically implemented by special stator winding configurations.

These are series and parallel winding connections, equalising winding connections, dual-set of winding configurations and single set of winding configurations. Smith and Dorrell [1] have analysed the UMP in ten-pole and six-pole induction machine by series winding and parallel winding connection. The UMP is greatly reduced by parallel connections due to the sinusoidal flux density distribution in the air-gap. Berman [2] took a different approach in stator winding connection which has an equalising connection with two parallel branches comprising three series-connected coils. The measured UMP was 25 times smaller than in the absence of the equalizing connections.

Dual set of winding configurations [3] was proposed by Chiba, A., Power, D.T., and Rahman, M.A. The primary winding carries the motor currents which drive the rotor, while the secondary winding carries the levitation currents which produce controllable transverse force. The basic principle of radial force production using dual set of stator winding is that Flux distribution due to the main torque producing motor supply is a dominating 4-pole magnetic field and that due to the levitation supply is a 2-pole magnetic field. These fluxes are in the same direction in the air gap and thus, air gap flux density is increased. In the opposite air gap, the flux direction is opposite, and thus, flux density is decreased. Therefore, superposition of the two-pole levitation field to the motor field results in an unbalanced flux distribution in the air gap. This unbalanced flux distribution results in a net radial- magnetic force in the direction of highest magnetic flux. Opposite-directed force can be obtained by changing the direction of levitation current. The main drawback of these methods is that it occupies some space in the stator slots which otherwise could have been used for torque production. Laiho, A., Tammi, K., Orivuori, J., Sinervo, A., Zenger, K., and Arkkio, A [4 & 5] have used dual set of winding for flexural vibration control with an built in actuator in a two-pole induction machine. During recent years active vibration control become alternative for passive or semi-passive vibration control. Sinervo, A., Jokela, T., and Arkkio, A. [6] have used the unipolar actuator to mitigate the unipolar fluxes in the two-pole induction machine which causes the UMP.

In single set of winding configurations the main torque producing winding can be used to control the UMP. This type of winding possesses advantages such as simpler construction, requiring only one set of winding, relatively low power loss. Khoo's [7] bridge configured winding and Chiba's [8] middle point current injection type winding belong to the single set of winding configuration.

In middle-point-current-injection type of stator winding [8], when the levitation field is superimposed to the motor field, the flux density decreases in one side of air gap while it is unchanged in the opposite side of air gap. The unbalance in the flux distribution results in the radial force in the direction of highest magnetic flux. It may be pointed out that the resultant radial force, in this winding configuration, is about a half of that in the dual set stator winding motor, because the flux unbalance occurs in only one air gap.

The bridge configured winding first introduced by Khoo [7] overcomes the drawback associated with dual set of stator secondary windings. The method uses the main torque producing winding to suppress the UMP due to eccentricity. Thus, for the same performance the machine with the bridge configured windings will be smaller in size and weight than those with dual set of stator windings. The principal feature of the bridge configured winding is that the currents responsible for torque production are divided into two parallel paths in each phase. However, it is mandatory that an appropriate isolation between the levitation supply and the mains must be enforced for the bridge connection to work [9]. Otherwise both supplies will be shorted. When the bridge connection has more than one levitation supply, not only must each levitation supply be isolated from the mains, they must also be isolated from each other. For an example, in a 4-pole machine, when the motor current flows, a dominant 4-pole magnetic field is generated. When the active control is injected, using a low-voltage and low-current bidirectional power supply a two-pole levitation field is generated. Superposition of the 2-pole field to the 4-pole motor field results in an unbalanced magnetic flux distribution in the air gap. This gives rise to a net lateral force in the direction of highest magnetic flux. Laiho, A., Kalita, K., Tammi, K., and Garvey, S.D developed an analytical model for calculating this lateral force in the airgap [10].

Present paper is based on bridge configured winding scheme. The feature which makes the bridge winding different from the other active methods for reducing UMP is its provision for passive control. Passive control of UMP can be accomplished by short circuiting the additional pairs of terminals or closing the bridge. No current will flow across the bridge if the rotor is concentric and the stator MMF is symmetric (flux field is uniformly distributed) i.e. bridge currents are zero. Any unbalance of field due to eccentricity will induce an EMF tending to drive currents in the closed circuit such that an MMF comes to exist opposing the rate of change of this field. The currents flowing across the bridge are known as equalizing currents. Therefore, these equalizing currents are the measures of unbalance of a particular machine at its operating conditions. Authors have extended the work done by A. Laiho, K.Kalita, K.Tammi, and S.D.Garvey, S.D. [10] where analysis was done on forces exerted on the rotor by sinusoidal bridge supplies. In the present work an experimental setup has been developed and bridge currents have been measured which is the sign of an unbalance present in the system.

## II. EXPERIMENTAL SETUP

A common 37kW induction motor is used for the experimental setup shown in Fig. 1.

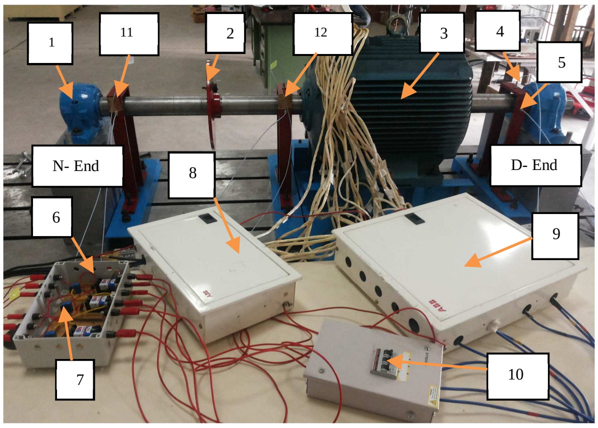


Fig. 1. A modified 37kW induction machine for the experimental setup.

1 – Bearing Housing, 2 – Perforated Disc, 3 – Test Machine, 4 – Sensor for Vertical Displacement, 5 – Sensor for Horizontal Displacement, 6 – Current transducer kit, 7 – Hall sensor, 8 – Main Supply Connections, 9 – Bridge winding Connections, 10 – Switches for Bridge Connections, 11 – Location 1 for measuring the rotor responses, 12 – Location 2 for measuring the rotor responses.

The main parameters of the induction machine are shown in Table I. The existing winding of the motor has been removed and replaced by a new bridge configured based winding. Table II, shows the stator, rotor and winding parameters. The existing stator winding is a double layered full pitch winding which has 4 strands and 11 turns with a coil pitch of 15. The existing main coil winding is modified to 3 strands and 11 turns of same wire diameter in order to accommodate the search coil winding over the main coil winding. The new bridge configured winding is a distributed, double layered; chorded winding as shown in Fig. 2.

TABLE I. THE MAIN PARAMETERS OF THE INDUCTION MACHINE USED IN THE EXPERIMENTS

| Parameter | Value |
|---|---|
| Supply frequency | 50Hz |
| Rated voltage | 415 V |
| Rated Speed | 1470 rpm |
| No of Phases | 3 |
| No of poles | 4 |
| Rotor Core mass | 46.46 kg |
| Rotor shaft length | 1.8 m |
| Radial air gap length | 1.25 mm |

TABLE II. STATOR, ROTOR AND WINDING PARAMETERS

| Parameter | Value |
|---|---|
| Stator outer diameter | 350mm |
| Stator inner diameter | 221mm |
| Stator core length | 212mm |
| Rotor outer diameter | 218.5mm |
| Rotor inner diameter | 75mm |
| Rotor skew | 5° |
| Number of stator slots | 60 |
| Number of rotor slots | 48 |
| Number of winding layer | 2 |
| Number of parallel branches (per phase) | 2 |
| Number of turns | 11 |
| Number of strands | 3 |
| Coil wire diameter | 1.22mm |
| Winding connection | Bridge connection |

Search coils can be used to find the pole positions of 2-pole, 4-pole and 6-poles of the main winding fields as well as rotor fields. The modified main coil winding and search coil winding are placed on the same slots of the stator with four pole main winding which fills 75% of the slot and other 25% is filled by the search coil winding. Search coil has two-pole, four-pole and six-pole winding.

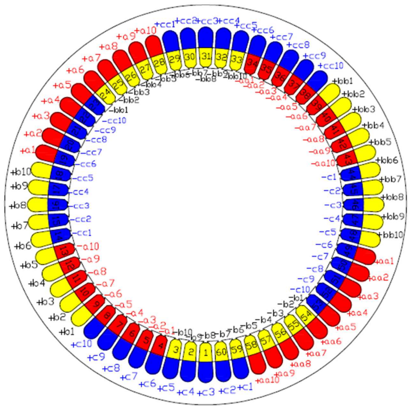

Fig. 2. A winding scheme of a distributed, double layered winding.

The leads of the search coils can be used to get the pole positions by means of the voltages induced in the search coils. Rotor shaft has been changed to make the system flexible. However, the rotordynamics tests are not carried out yet. Initially motor had 0.8m long rotor (as shown in Fig. 3) which is replaced by 1.8m long rotor as shown in Fig. 4. The shaft is supported by external bearings at both the ends. One backup bearing with 0.5mm clearance has been put inside the end-shields at non-driving end for safety purpose. The rotor core has been fixed on the shaft at 140 mm from the end shield of the non-driving end. The mass of the rotor core is 46.56 kg. Three hall sensors have been used to measure the current flowing in bridge connection as shown in Fig. 5.

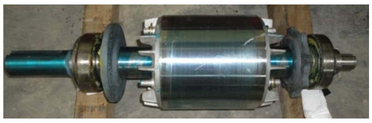

Fig. 3. A standard shaft of length 0.8m.

Fig. 4. A extended rotor (length 1800mm) used in the test machine.

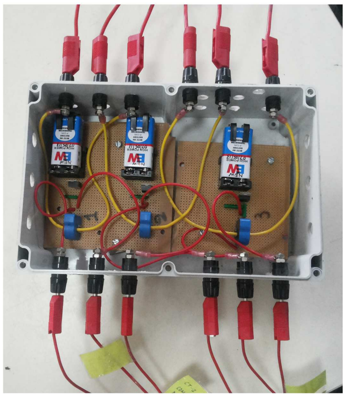

Fig. 5. A current transducer kit.

## III. RESULTS AND DISCUSSION

Readings were taken when 15 and 20 Hz of excitation has been given to the system. Initially when bridges were off, it has been observed that there is no current flow across the bridge. Bridge currents have been observed across the bridge connection as soon as bridge connections were short circuited. Hall effect closed loop (compensated) multi-range current transducers (LTS 15NP) are used to measure the currents. The outputs of these current transducers were connected to the NI DAQ system using SCB 68 connector block and PXI-6221. The samples have been measured at the rate of 6k sample/s. The outputs of these current transducers are voltage which has a linear relation with current. Bridge currents have been measured in two cases, in 1st case bridge currents have been measured when there is no mass in the disc and in 2nd case bridge currents have been measured when 150gm of mass has been placed in the disc. FFT of these measured current has been done in MATLAB and plotted as shown in Fig. 6 to Fig. 17 for all the three phases. Fig. 6 to Fig. 11 shows the measured equalising currents in frequency domain for a supply voltage of 15 and 20 Hz. Fig. 12 to Fig. 17 shows the comparison of bridge currents with and without mass. The main frequency components of equalising currents are $\frac{1}{2} f_S$, $f_S$ and $\frac{3}{2} f_S$, where $f_S$ is the frequency of the supply voltage.

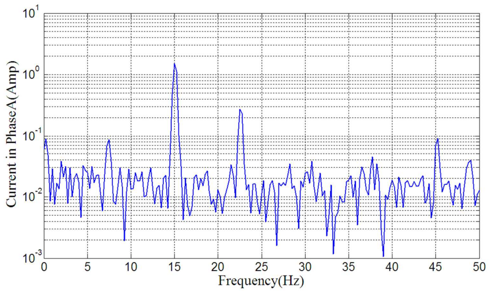


Fig. 6. Bridge current in Phase A at 15Hz supply frequency in frequency domain without mass in the disc

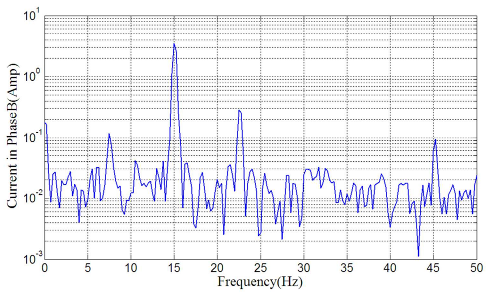


Fig. 7. Bridge current in Phase B at 15Hz supply frequency in frequency domain without mass in the disc

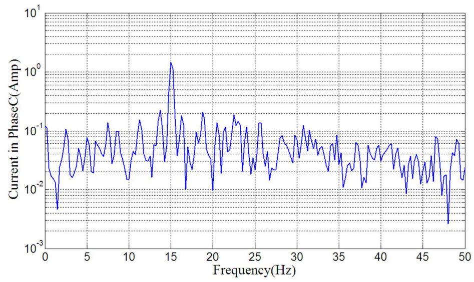


Fig. 8. Bridge current in Phase C at 15Hz supply frequency in frequency domain without mass in the disc

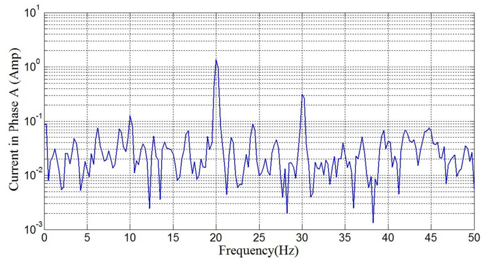


Fig. 9. Bridge current in Phase A at 20Hz supply frequency in frequency domain without mass in the disc

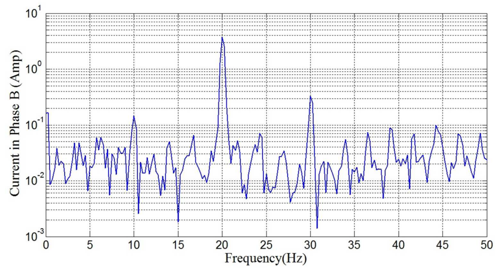


Fig. 10. Bridge current in Phase B at 20Hz supply frequency in frequency domain without mass in the disc

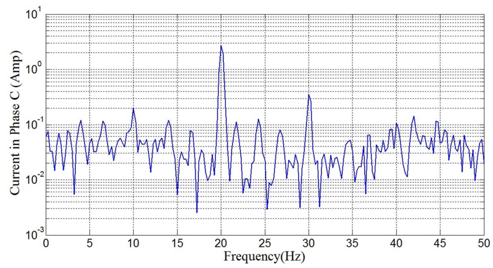


Fig. 11. Bridge current in Phase C at 20Hz supply frequency in frequency domain without mass in the disc

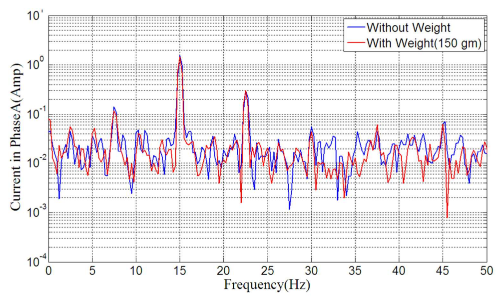


Fig. 12. Phase A current at 15Hz supply frequency with a mass of 150grams

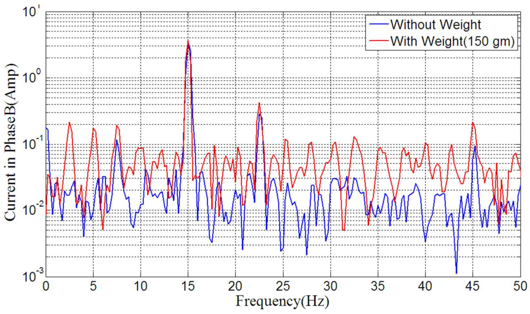


Fig. 13. Phase B current at 15Hz supply frequency with a mass of 150grams

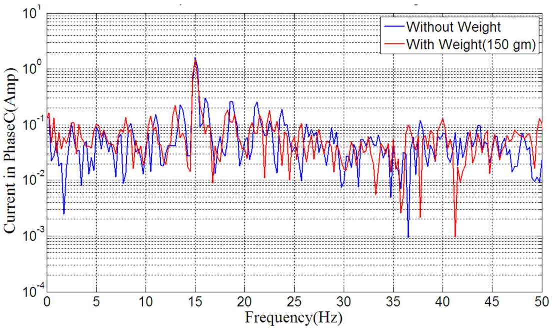


Fig. 14. Phase C current at 15Hz supply frequency with a mass of 150grams

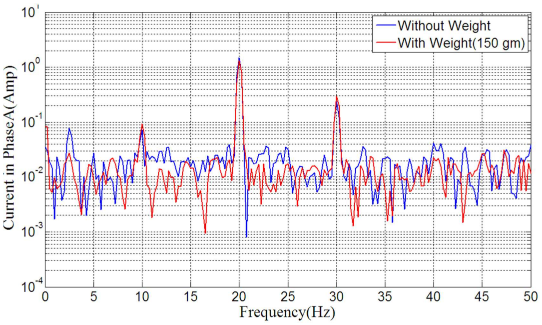


Fig. 15. Phase A current at 20Hz supply frequency with a mass of 150grams

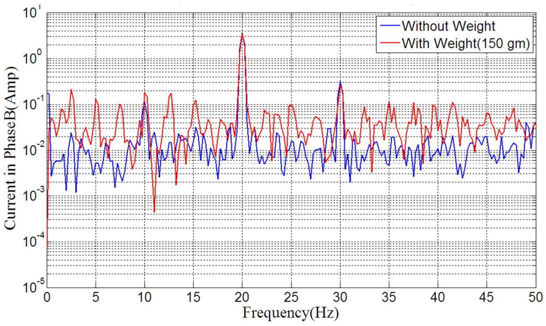


Fig. 16. Phase B current at 20Hz supply frequency with a mass of 150grams

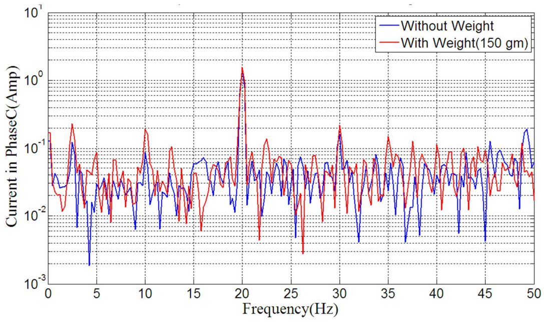


Fig. 17. Phase C current at 20Hz supply frequency with a mass of 150grams

The rotor response has been measured using the eddy current proximity sensor. Four Sensors have been put at two locations, Two at one location (near N-end bearing) one in x-direction and another in y-direction (Location 1 in Fig. 1) and two at other (N-end, end shield cover) location (Location 2 in Fig. 1). Output of the proximity sensor is voltage which has a linear relation with the response. Measurement has been done using the multifunction PXI-6221. Measured data has been plotted in MATLAB as shown in Fig. 18 and Fig. 19. From these figures it can be seen that Passive control of unbalance can be accomplished by short circuiting or closing the bridge.

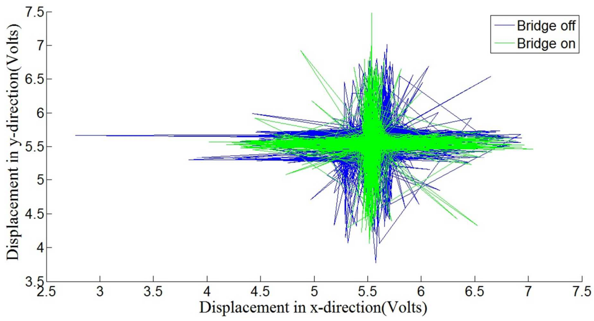


Fig. 18. xy plot at location1

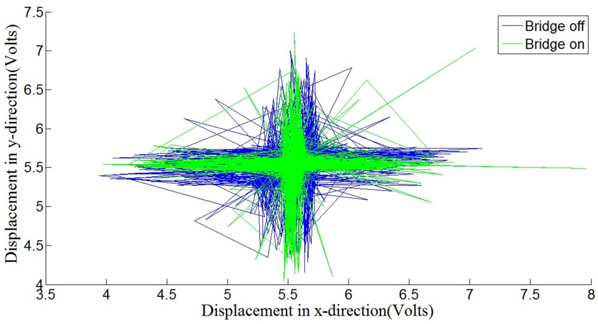


Fig. 19. xy plot at location1

It can be clearly observed from the Fig. 6 to Fig. 11 that bridge current is present in the system when there is no mass in the disc. This shows that system already has some unbalance. Difference in bridge current can be observed in Fig. 12 to Fig. 17 when some mass has been added to the disc. Though this difference in current is not significant but it can be said with this that bridge current changes with the change in unbalance in the system. We will not be able to quantify this change at this moment as there is no significant change. One reason may be the weight is not enough to produce unbalance force in the air gap which will induce currents in the bridge.

## IV. CONCLUSION

An experimental setup has been built up to investigate the electromechanical interaction of an induction machine. The design procedure of the setup has been described. The fact that equalising or bridge current flows in the system due to the unbalance present in the system has been demonstrated experimentally. The main frequency components of equalising currents are $\frac{1}{2} f_S$, $f_S$ and $\frac{3}{2} f_S$, where $f_S$ is the frequency of the supply voltage. The passive control of UMP can be accomplished by short circuiting the additional pairs of terminals or closing the bridge. The main purpose of the present paper is to show that with the measurement of bridge current it can be said that the system has any unbalance or not. If there is any bridge current in the circuit then the system has unbalance else it has no unbalance. It has been also shown that bridge current changes with respect to change in the unbalance.

## REFERENCES


[1] A.C. Smith, D.G. Dorrell, "Calculation and measurement of unbalanced magnetic pull in cage induction motors with eccentric rotors – Experimetal Investigation," IEE Proceedings on Electric Power Applications, pp. 202 – 210, 1996.

[2] M. Berman, "On the Reduction of Magnetic Pull in Induction Motors with Off-Centre Rotor," IEEE Transaction on Industry Applications, pp. 343-350, 1999.

[3] A. Chiba, D.T. Power, and M.A. Rahman, "Characteristics of a bearingless induction motor," IEEE Transaction on Magnetics, 27(6), pp. 5199-5201, 1991.

[4] A. Laiho, K. Tammi, J. Orivuori, A. Sinervo, K. Zenger, and A. Arkkio, "Electromechanical Interaction in Eccentric-Rotor Cage induction Machine Equipped with a self-Bearing Force Actuator," Journal of System Design and Dynamics 3, No-4, pp. 519-529, 2009.

[5] A. Laiho, A. Sinervo, J. Orivuori, K. Tammi, A. Arkkio, and K. Zenger, "Attenuation of Harmonic Rotor Vibration in a Cage Rotor Induction Machine by a self-Bearing Force Actuator," IEEE Transaction on Magnetics 45,No-12, pp. 5388-5398, 2009.

[6] A. Sinervo, T. Jokela, and A. Arkkio, "Controlling rotor vibrations of a two-pole induction machine with unipolar actuator," IEEE Transaction on Magnetics, pp. 1-7, 2011.

[7] W.K.S. Khoo, "Bridge configured winding for poly-phase self-bearing machines," IEEE Transactions on Magnetics, pp. 1249-1295, 2005.

[8] A. Chiba, K. Sotome, Y. Iiyama, and K. Rahman, "A Novel Middle-point-current-injection-type Bearing-less PM Synchronous Motor for Vibration Suppression," IEEE Transactions on Industrial Applications, 47(4), pp. 1700-1706, 2011.

[9] W.K.S. Khoo, K.Kalita, K., and Garvey, S.D, "Practical Implementation of the Bridge Configured Winding for Production of Controllable Transverse Forces in Electrical Machines," IEEE Transactions on Magnetics, 47(6), pp. 1712–1718, 2011.

[10] A. Laiho, K. Kalita, K. Tammi, and S.D. Garvey, S.D. "Dynamics of Bridge-Configured Built-in Force Actuator for Vibration Control in Four-Pole Cage Induction Machine," 18th International Congress on Sound and Vibrations, ICSV18, Rio de Janeiro, Brazil, pp. 10–14 2011.