New Bearingless Permanent Magnet Machine with Multiple-Modules for Direct-Drive Wind Turbines

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1. Introduction

The aim of this paper is to verify a new configuration of bearingless permanent magnet (PM) machine with multiple-modules that would enable to reduce bearing failures, and to facilitate manufacture and maintenance of direct-drive wind turbines.

In wind turbines, bearing failures have been a continuing problem and a significant proportion of all failures. Bearing-related downtime is among the highest of all components of wind turbines. The location of wind turbines is moving offshore because of higher wind speeds and less turbulence, and limited space to install the turbines on land and onshore. However, to access offshore is difficult thus the wind turbines with high reliability and availability are required offshore.

Direct-drive wind generators have been discussed as the generator type with higher energy yield than geared generators. However, direct-drive generators require large diameter, which results in large mass and high cost, in order to get high torque rating compared to geared generators. To construct direct-drive generators with large diameter as a single module (one-body structure) is disadvantageous in terms of manufacture and maintenance.

In this paper, a ring-shaped bearingless PM machine with multiple-modules is discussed as a promising generator to reduce bearing failures and to facilitate manufacture and maintenance.

2. Approach

A. Why bearingless machine concept?

To reduce bearing failures of wind generators, the use of magnetic bearings, bearingless drive machine or hydraulic bearings could be an alternative instead of mechanical bearings. Conventional bearingless drive machines need to control both the torque with torque winding and the bearing force with bearing winding. A significant feature of the new bearingless drive machine compared to the conventional bearingless machine is that the main windings are used to simultaneously produce and control both the torque and the bearing force.

B. Why modular concept?

Considering the production, transportation, installation, operation and maintenance of wind generators, the following generator constructions can be promising solutions for large direct-drive wind turbines:

- a modular construction that can be easily assembled, separated, transported and installed;
- a modular construction of which module can work individually.

This paper begins with a description of the new bearingless PM machine with multiple-modules. The machine is a transverse flux PM machine with double-sided air-gaps and multiple-modules of rotor and stator. In order to identify the thrust force and the normal force of the machine as a function of rotor position, air-gap length and magneto-motive force by currents, the forces of a side of a stator module are obtained through three-dimensional finite element analyses (3D FEA). In order to implement the machine, a rotating TFPM generator with multiple-modules is built, and the proposed bearingless drive concept is achieved experimentally.

3. Main body

A. TFPM machine with multiple-modules

Various configurations of TFPM machines have been proposed and discussed in a number of research papers. TFPM machines with flux-concentrating configurations have higher force density which results in volume reduction and consequently mass reduction. However, conventional flux-concentrating TFPM machines have disadvantages, and unsuitable configurations of those machines for large direct-drive wind turbines can be summarized as follows:

- double windings
- ring-windings with a large diameter
- large size of iron cores and magnets
- using the bonding method to affix magnets
- assembling magnets and rotor cores in tangential stacking
- difficulties in mass production

In order to overcome the disadvantages of the flux-concentrating TFPM machine, the following configurations can be discussed as suitable configurations for large direct-drive wind turbines:

- flux-concentrating TFPM machine with single-sided and single-winding configuration
- a multiple-module configuration of TFPM machine with multiple-slots per phase
- racetrack-shaped windings instead of ring-windings
- claw pole configuration of TFPM machine with an increased iron core area
- segmented iron cores and segmented magnets in order to facilitate manufacture
- modular structures of the rotor and stator in order to facilitate manufacture and maintenance

Fig. 1 depicts a sketch of the proposed flux-concentrating TFPM machine with the configuration of single-sided air-gap, single-winding, racetrack-shaped winding, claw poles, segmented iron cores, segmented magnets, multiple-modules and multiple-slots per phase.

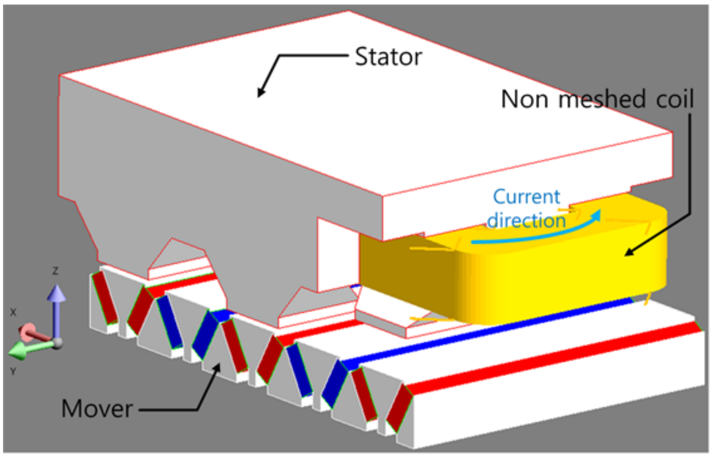


Fig. 1 Sketch of the proposed TFPM machine configuration

B. Finite element analysis

In order to identify the thrust force and the normal force of the machine in terms of air-gap length, current and rotor position, the 3D-FEA is done. The model for the 3D-FEA and the dimensions of the machine are represented in Fig. 2, and the mesh of the 3D-FEA model is depicted as Fig. 3.

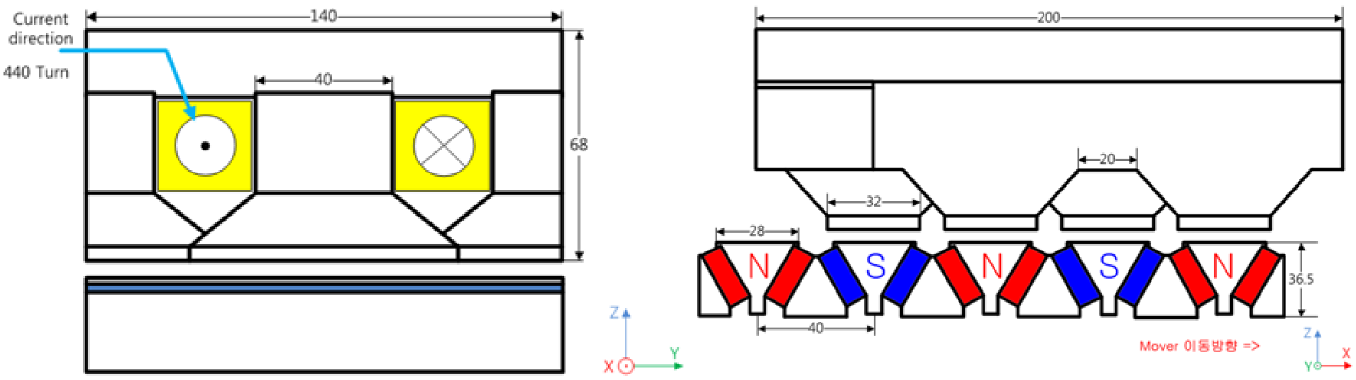


Fig. 2 3D-FEA analysis model

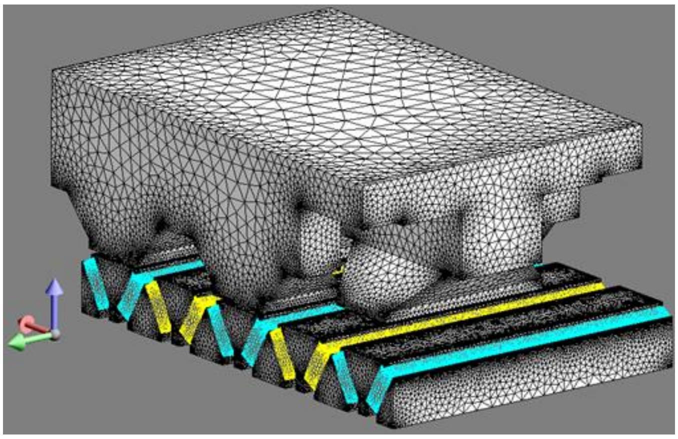
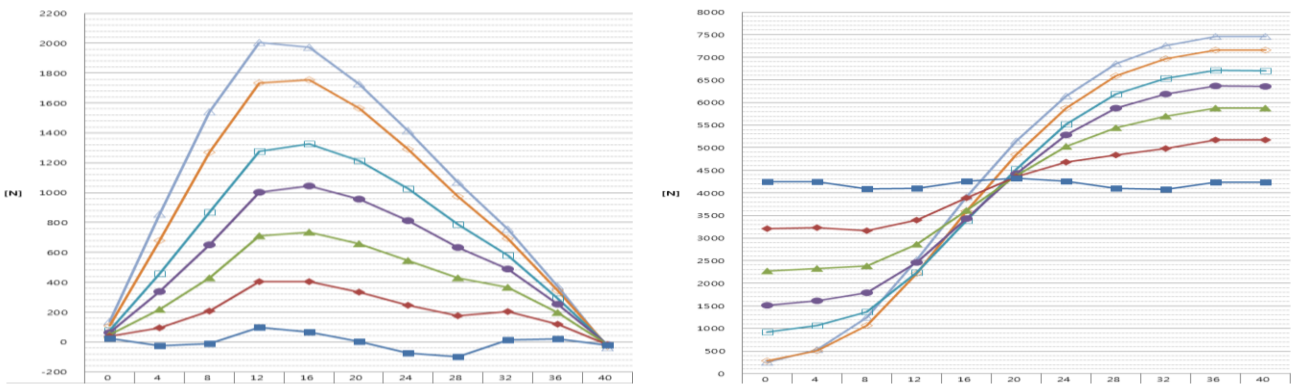


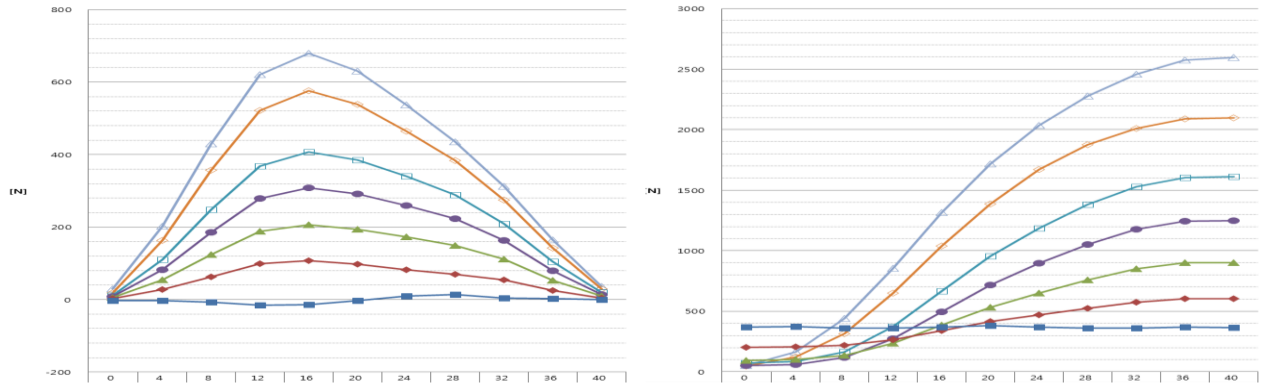
Fig. 3 Mesh model of the TFPM machine

The 3D-FEA results of the thrust force and the normal force as a function of current and rotor position are represented for different air-gap length, 2mm and 6mm, in Fig. 4 and Fig. 5.



(a) Thrust force (b) Normal force

Fig. 4 Thrust force and normal force at 2mm air-gap length by 3D-FEA



(a) Thrust force (b) Normal force

Fig. 5 Thrust force and normal force at 6mm air-gap length by 3D-FEA

C. Bearingless control algorithm of the proposed machine

In this paper, an algorithm of phase angle shift is applied for the proposed bearingless TFPM machine in order to control the air-gap length by controlling the normal forces between the rotor and stator. Using the results of the 3D-FEA, the variation of those forces can be represented as a function of phase shift angle, rotor position, air-gap length and magneto-motive force by currents. <u>The sum of those forces of three-phase on one-side of the machine will be included in the full paper.</u> The normal force at 6mm air-gap length could be controlled to be larger than the force at 2mm air-gap length by shifting the phase angles and by changing the magneto-motive forces. Therefore, it is possible to achieve the air-gap controls of both sides to be equal when the air-gap 1 is not equal with air-gap 2. The control block diagram for the air-gap control and the rotor position control is represented as Fig. 6. The air-gap length reference is produced by the proportional-integral-derivative (PID) controllers. After operating the gap controller, the currents to control the air-gap length are generated by shifting the phase angles. These signals are added to the outputs of the PI speed controller. The phase currents to control the normal forces and the air-gap length can be written as (1) and (2) as a function of the phase shift angle θ_{shift}.

$$I^*_{abc\_left} = I^*_{mag} \cdot \sin\left(\theta + n \cdot \frac{2\pi}{3} + \theta_{shift}\right) \qquad (1)$$

$$I^*_{abc\_right} = -I^*_{mag} \cdot \sin\left(\theta + n \cdot \frac{2\pi}{3} - \theta_{shift}\right) \qquad (2)$$

Where, n is 0 for A-phase, 1 for B-phase and -1 for C-phase.

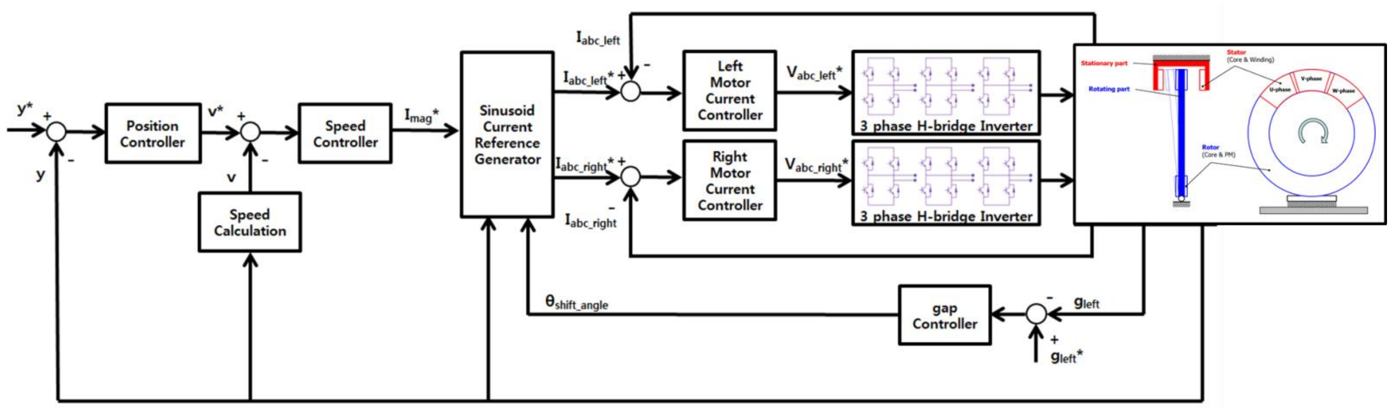


Fig. 6 Control block diagram of the bearingless TFPM machine

D. Experimental verification

In order to verify the concept of the proposed bearingless drive TFPM generator, the experimental setup can be constructed as Fig. 7. The mean diameter of the machine is 1.4m. The machine consists of multiple-modules of the stator and the rotor, and a hinge and roller mechanism is set on between the bottom of rotor and the stationary part. Fig. 8 depicts the TFPM machine built. Fig. 9 represents the experimental results of the TFPM machine in a motor mode. (The results in a generator mode will be included in the full paper.) The air-gap command is 3.5mm at 10rpm, and the maximum displacement of the air-gap is 0.4mm at the same speed.

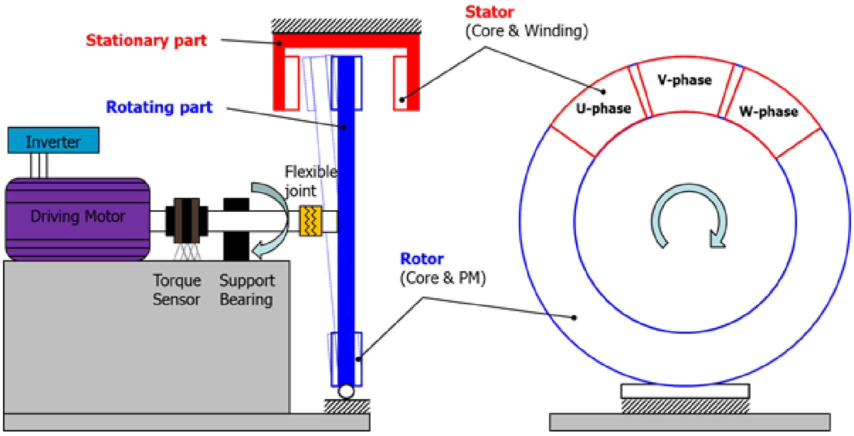


Fig. 7 Sketch of experimental setup of PM generator with multiple-modules

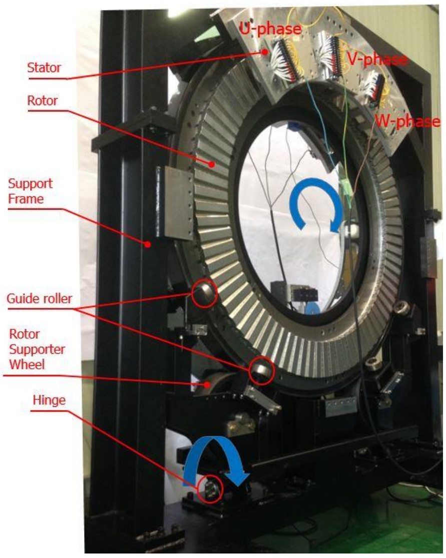


Fig. 8 Photo of TFPM machine built

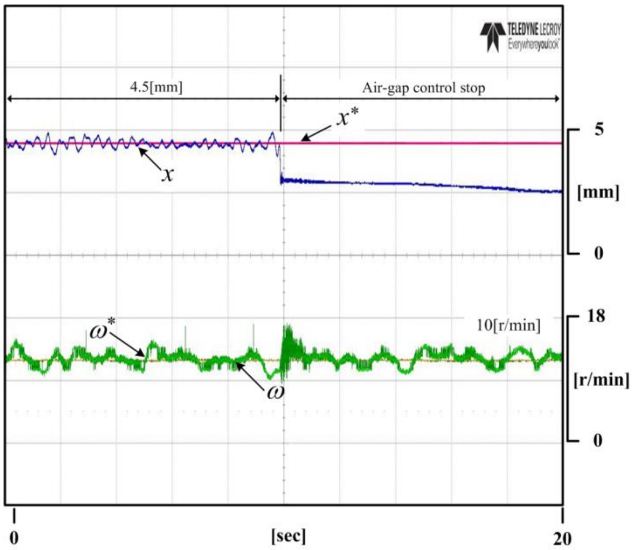


Fig. 9 Experimental results

4. Conclusions

A new bearingless transverse flux permanent magnet (TFPM) machine with multiple-modules, flux-concentrating configuration and double-sided air-gaps has been discussed as a promising concept to reduce bearing failure and to facilitate manufacture and maintenance of direct-drive wind turbines. The feature of the proposed bearingless machine is that the main windings are used to simultaneously produce and control both the torque and the bearing force. The thrust force and the normal force in a linearized model have been obtained through the three-dimensional finite element analyses (3D-FEA) in order to identify the forces as a function of the air-gap length, the rotor position and the currents. An algorithm of phase shift angle has been applied to simultaneously control the air-gap length by controlling the normal force and the rotor position by controlling the torque. The new bearingless drive machine concept has been experimentally verified, and the maximum displacement of the air-gap length was 0.4mm which is about 9% of the air-gap length, 4.5mm in rotating the rotor with 1.4m diameter at 10rpm.

In the full paper, the results in the generator mode of the bearingless TFPM machine will be included.

5. Learning objectives

- To state problems of generator systems for direct-drive (offshore) wind turbines
- To define promising generator concept to reduce bearing failures and to facilitate manufacture and maintenance
- To experimentally verify a new bearingless TFPM machine concept with multiple-modules to make large direct-drive wind generators more attractive for industry use

References

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