PhD Public Defence

**Title:** Design and Analysis of Magnetic Transmission Devices for Low-Speed High-Torque Application

**Location:** Pontoppidanstræde 101, room 23

**Time:** Monday 6 November 2017 at 13.00

**PhD defendant:** Xiaoxu Zhang

**Supervisor:** Professor Zhe Chen

**Moderator:** Associate Professor Weihao Hu

**Opponents:**
- Associate Professor Kaiyuan Lu, Dept. of Energy Technology, Aalborg University (Chairman)
- Associate Professor Henk Polinder, Delft University of Technology, the Netherlands
- Professor Ed Spooner, University of Durham, UK

All are welcome. The defence will be in English.

After the defence there will be an informal reception in Pontoppidanstræde 111 (coffee room).
Abstract:
There is an increasing demand for low-speed and high-torque transmission from wind power generation to ship propulsion. Generally, the low-speed and high-torque transmission system could be classified into the mechanical-geared-drive solution and direct-drive solution. The mechanical-geared-drive solution usually suffers from the issues associated with the mechanical gearbox, such as the need for lubrication, wear between contacting surfaces, noise and vibration, etc. Although the direct-drive solution could operate without mechanical gearbox, the direct-drive machines rotate at low speed, which would lead to a bulky size. The purpose of this PhD project is to propose some new coaxial magnetic gears (CMGs) and magnetically-geared machines (MGMs), which could be introduced into the low-speed high-torque applications to solve or artfully avoid the above issues.

Firstly, the analytical model of the CMG, based on subdomain modeling technique, is built up. The magnetic behaviors in the CMG are described by Maxwell equations in terms of the magnetic vector potentials \( A \) in 2-D polar coordinates. By applying the interface constraints, the magnetic problems in the CMG could be represented by a matrix equation. The analytical solution could be achieved by using numerical computation. After that, the influence of the key design parameters on torque density and unbalanced magnetic force are investigated, respectively. However, for the CMGs in the high-torque applications, the increased unit capacity may result in significant growth of the subdomains, so that the dimension of the matrix equation becomes large. It is inevitable to increase the processing time of the analytical subdomain model, which makes the subdomain technique not present too many advantages over the FE calculation in terms of computational efficiency. Therefore, this PhD project puts efforts on the matrix dimension reduction and makes attempts to make the most of the interface constraints in order to achieve a significant improvement on the computational cost.

Secondly, for ease of the integration of the CMG with electrical machines, this PhD project aims at proposing a novel CMG, which will not increase the mechanical complexity after the combination with a permanent magnet (PM) brushless machine. The prominent feature of the proposed CMG is the introduction of a slotted stator. The teeth on the stator could function as the same as the modulating pole-pieces in the conventional CMG. The corresponding integrated MGM can then be achieved by inserting the armature windings into the stator slots. The configuration, harmonic analysis, and torque capability of the proposed CMG are studied in comparison with the conventional CMG. The operating principle and electromagnetic performance of the proposed MGM are investigated by dividing it into one vernier PM machine, one PM brushless machine and one proposed CMG. The results show that the developed integrated MGM exhibits good torque capability and high power factor.

Thirdly, a dual-flux-modulator CMG (DFM-CMG), characterized by high torque capability and high PM utilization, is proposed. The DFM-CMG adopts spoke-type outer PM rotor and introduces an auxiliary flux modulator placed on the outmost layer. The harmonic analysis with detailed theoretical derivation is performed to reveal that the ferromagnetic pole-shoes on the spoke-type outer PM rotor could modulate the flux density distribution as well and create a nested magnetic-gearing effect. More useful harmonics are thus generated in the air-gaps to contribute to the torque production. The effect of the auxiliary flux modulator on the flux density distribution is also studied by finite element (FE) analysis. Due to the presence of the auxiliary flux modulator, the flux leakage is suppressed and the useful harmonics are amplified. A quantitative comparison among the surface-mounted CMG (SM-CMG), spoke-type CMG (ST-CMG) and DFM-CMG is made to investigate the performance improvement of the DFM-CMG. The presence of the auxiliary flux modulator has been verified to be able to improve the torque production by FE analysis of 44% growth and experimental test of 41% growth, respectively. Finally, by adding the armature windings into the stator slots of the auxiliary flux modulator, a dual-flux-modulator MGM (DFM-MGM) is achieved. The back electromotive force, torque performance, and power factor of the DFM-MGM are investigated by the FE analysis and finally verified by the experimental test.