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# Electromechanical Dynamics Analysis of Pole-Piece Rotors in Pseudo Direct-Drive Wind Turbine Generators

Michiel Desmedt, Jianning Dong, Faisal Wani, Pavol Bauer, Henk Polinder

***Abstract*—This paper analyses the electromechanical dynamics of the pole-piece rotors in a pseudo direct-drive wind turbine generator. The investigated generator has a rated power of 10 MW and was designed in the INNWIND.EU project. One way coupled finite element analysis (FEA) was used to calculate the rotor dynamic defections caused by electromagnetic forces in the air gap. Results show that the deflection exceeds the air gap length which is not mechanically feasible. To solve the problem, three structural modifications are proposed and tested in FEA to reduce the pole piece deflection significantly. The results of the three solutions are compared to idenfity the most promising one. It shows that a ribbed rotor piece topology is the most suitable option because it achieves a reasonable tradeoff between the torque generation and mechanical deflection.**

***Index Terms*—wind turbine generator, pseudo direct-drive, permanent magnet generators, structural dynamics**

## I. INTRODUCTION

Wind energy is believed to be one of the most promising solution to limit global warming [1]. The wind power capacity is growing steadily year by year, especially in Europe [2]. The decreasing levelised cost of energy (LCoE) of wind energy is one of the reasons why it has become increasingly popular [3], but in order to further incentivize and increase its competitiveness, the LCoE should be decreased even further. There are several finished or ongoing projects on pushing new technological advances to further bring down wind energy LCoE in the coming decades.

The finished INNWIND.EU project has demonstrated how increasing wind turbine size can decrease the LCoE [4]. This is especially the case for offshore wind turbines, where maintenance is more expensive, making fewer bigger wind turbines more economically viable than a number of smaller wind turbines. This is why there is a clear trend showing the increasing size of offshore wind turbines.

Making wind turbines more reliable and thus reducing maintenance is of prime importance when trying to reduce the LCoE [5]. This is why a significant amount of offshore wind turbines nowadays use direct-drive generators instead of geared generators, as the gear is shown to be a high risk component in the drivetrain of a wind turbine [6], [7]. Due to the slow rotational speed of the rotor however, the generator has to provide a high torque, requiring a large diameter machine. With increasing size and mass, it becomes impractical to transport and install them, especially offshore. In order to keep the generator compact, the speed of the rotor should be increased in order to reduce the torque, and thus size of the generator for a certain rated power. Instead of using a mechanical gearbox which is prone to wear due to the meshing teeth, it is possible to transmit the forces contactless. This is the working principle of magnetic gears [8]–[11]. Using this kind of gearbox, most disadvantages of mechanical gearboxes are bypassed, and more compact generators can be used in wind turbines. The advantages of magnetic gears become even more apparent when it can be combined with a direct-drive machine in the same volume, which is consequently called a pseudo direct-drive (PDD) machine [12]–[14]. Due to its infancy, no established design rules or analytical models were developed yet which would enable optimisation. The INNWIND.EU project looked into this and came up with a design electromagnetically optimised for 10 and 20 MW wind turbines [15].

Because it is a part not seen in other machine topologies, one of the more complex subjects of research of PDD machines is the pole-piece rotor, which is used to modulate the magnetic fields between the stator and the high-speed rotor. This pole-piece rotor ideally consists of an array of high-permeability steel beams magnetically isolated from each other. Research has been done on different pole-piece rotor designs, focusing on magnetic performance and manufacturability, not mechanical behaviour [9], [16]. At the same time, research was also done focusing on the static mechanical optimisation of magnetic gears on MW-scale [15], [17].

While the dynamical mechanical behaviour of direct-drive wind turbine generator topology has already been investigated [18], [19], no research has been done yet on the deflections of the pole-piece rotor in PDD wind turbine generators, although the dynamic vibrations in the PDD generator is more problematic because of the piece-wise structure and more force harmonics. To compensate this research gap, this paper focuses on the dynamical electromagnetic analysis of the pole-piece rotor in a PDD generator proposed in the INNWIND.EU

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design. Possible modifications will also be introduced and analysed to make the INNWIND.EU design more feasible.

## II. GENERATOR STRUCTURE AND PARAMETERS

Figure 1 shows the drivetrain of a wind turbine using the PDD generator, where HS represents the high speed rotor, PP represents the pole-piece rotor. There are permanent magnets (PM) mounted on the surface of the HS rotor and the stator with different number of poles. The magnetic field produced by the magnets is modulated by the PP rotor. The wind turbine blades are coupled to the PP rotor, which is rotating at a slower speed compared to the HS rotor by a magnetic gear ratio.

The cross sectional view of a section of the investigated generator is shown in Figure 2. The generator is designed in the INNWIND.EU project and has a rated power of 10 MW and a gear ratio of 7.5. Main parameters of the generator are shown in Table I.

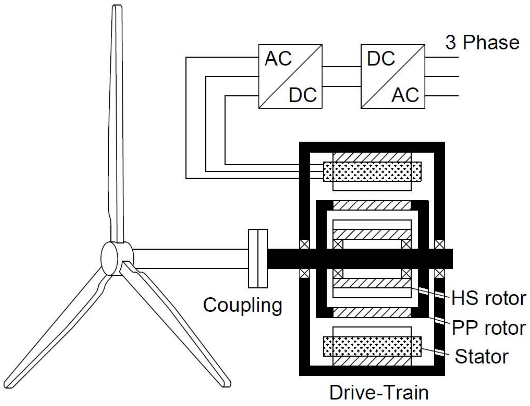


Fig. 1: Schematic of the wind turbine drivetrain using a PDD generator [15].

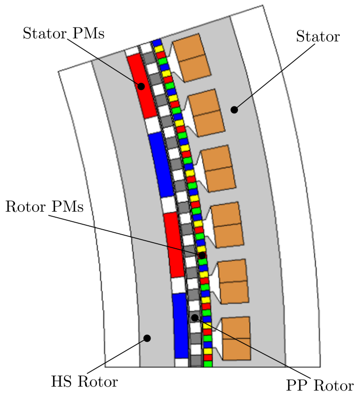


Fig. 2: One section of the investigated generator.

## III. MODELS AND METHODOLOGY

### A. Electromagnetic Model

Two-dimensional (2D) finite element analysis (FEA) model is used in this paper to analyse the electromagnetic performance of the PDD generator. The FEA model is implemented in COMSOL Multiphysics. The flux density waveforms in the inner air gap and the outer air gap are compared to those presented in the INNWIND.EU project report [4]. Good agreements have been obtained. Since the model is 2D, the ending effect and any variations along the axial direction are not considered.

TABLE I: Main Parameters of Investigated PDD Wind Turbine Generator [15]

| Quantity | Value | Unit |
|---|---|---|
| Rated power | 10 | MW |
| Rated speed of pole-piece rotor | 9.65 | rpm |
| Rated torque on the pole-piece rotor | 9.9 | MNm |
| Analytical pullout torque | 11.9 | MNm |
| Rated electrical output frequency | 48.25 | Hz |
| Gear ratio | 7.5 | - |
| Pole-pairs on high-speed rotor per section | 2 | - |
| Pole-pairs on stator per section | 13 | - |
| Halbach segments per pole-pair on the stator | 4 | - |
| Pole-pieces per section | 15 | - |
| Number of identical sections | 20 | - |
| Pole-piece slot opening angle | $\pi/300$ | rad |
| Airgap diameter | 6.0 | m |
| Radial height of pole-pieces | 31.4 | mm |
| Radial thickness of high-speed rotor PMs | 39.8 | mm |
| Radial thickness of stator PMs | 25.2 | mm |
| Length of inner air gap | 6.0 | mm |
| Length of outer air gap | 6.0 | mm |
| Active axial length | 1.66 | m |
| High-speed rotor pole arc to pole pitch ratio | 0.8 | - |
| Remanence of PMs | 1.25 | T |
| Relative recoil permeability of PMs | 1.05 | - |
| Copper packing factor | 0.5 | - |
| Current density at rated power | 2.0 | $\mathrm{A_{RMS}\ mm^{-2}}$ |
| Slot area | 0.0071 | $\mathrm{m^2}$ |
| Radial teeth length | 0.08 | m |
| Yoke thickness | 0.1 | m |
| Salient pole radial thickness | 0.03 | m |
| Stator pole arc to pole pitch ratio | 0.6 | - |

### B. Structural Dynamics Model

The pole-pieces are modelled in FEA as simple beams with a square cross-section. Both ends of the beams are assumed to be fixed, and the electromagnetic forces are assumed to be uniformly distributed along the pole-pieces. The geometry of the model is shown in Figure 3.

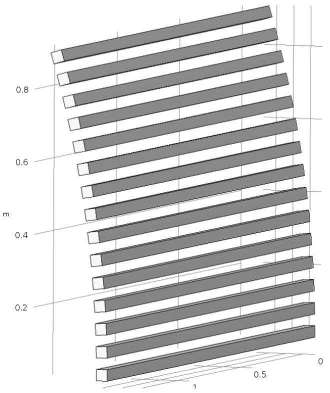


Fig. 3: Geometry of the structural dynamics model.

To validate the FEA model, first 5 natural frequencies obtained from the FEA are compared to the analytically computed frequencies, as shown in Table II. The analytical method used is presented in [20]. It can be seen the error is within 2%.

TABLE II: Analytical and FEA Results of the First 5 Natural Frequencies

| Mode | Analytical Results (Hz) | FEA Results (Hz) |
|---|---|---|
| 1 | 59.4 | 60.5 |
| 2 | 165 | 167 |
| 3 | 323 | 326 |
| 4 | 535 | 538 |
| 5 | 799 | 803 |

### C. Analysis Method of Rotor Pole-Piece Dynamics

Time domain transient mechanical dynamics analysis coupled to the electromagnetic model is used to analyse the rotor pole-piece dynamics. The model is simulated with sufficient time till it reaches the steady state. As a result of the 2D electromagnetic model, only a one-way coupled analysis can be done. The deflection of the pole-pieces are calculated from the structural dynamics model by applying the electromagnetic force on them. However, the dependence of magnetic field on the pole-piece deflection is not considered. This means the larger the deflection, the less accurate the model becomes. Next to that, no losses are modelled in the electromagnetic model.

## IV. RESULTS AND IMPROVEMENTS

### A. Original Design

The pole-piece force can be extracted from the FEA model described in Section III. Figure 4 shows the force waveform on one pole piece in one symmetric period, consisting of 8 magnetic periods. It can be seen that the electromagnetic force in the radial and tangential direction reaches up to 18 kN and 19 kN respectively.

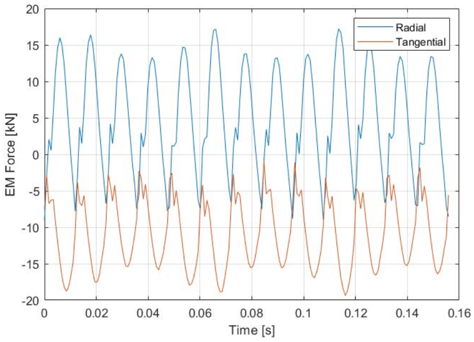


Fig. 4: Radial and tangential electromagnetic force on one of the pole-piece in time domain.

The force waveforms are decomposed into frequency spectra, as shown in Figure 5. Obviously, it shows two distinct peaks at 20 Hz and 83 Hz, as well as higher harmonics of the latter.

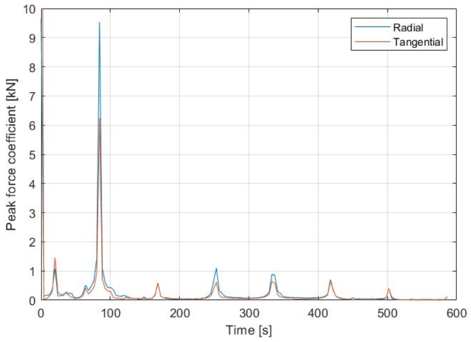


Fig. 5: Frequency spectra of the electromagnetic force on the pole-piece.

After applying the force to the structural dynamics model, the deflection of the pole-piece is calculated. The time domain result is shown in Figure 6. As can be seen, the largest radial deflection can reach more than 30 mm, which is more than 5 times the air gap length.

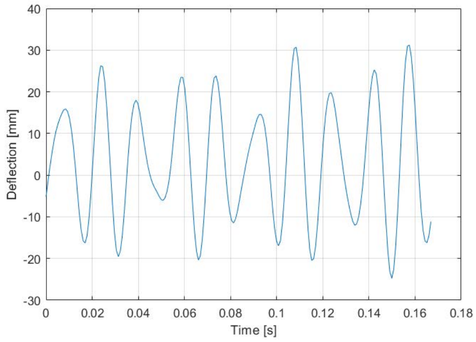


Fig. 6: Radial deflection of the original pole-piece design.

The deflection is analysed in the frequency domain to identify the reason. It can be seen from Figure 7 that there are two main frequency components at 20 Hz and 83 Hz. However, next to that, there is a large frequency component at 60 Hz, which is corresponding to the 1st order natural frequency. This resonance between the force component at 83 Hz and the natural frequency causes large deflections.

### B. Proposed Improvements

As the mechanical performance of the original design is too poor to actually result in a feasible physical model, it is necessary to look into ways of improving the mechanical behaviours.

Three new designs are selected to improve the original design. As shown in Figure 8, namely elongated pole-piece, bridged pole-piece and ribbed pole-piece.

*1) Elongated pole-piece:* It relies on an increase in pole-piece radial height, which drastically increases the radial area

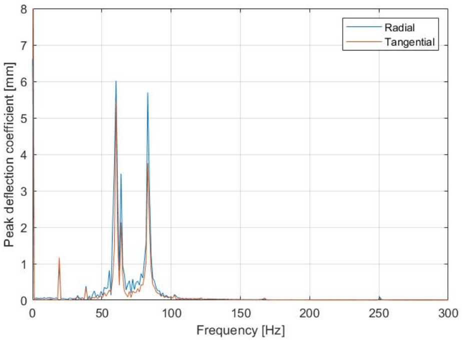


Fig. 7: Frequency spectra of the pole-piece deflections.

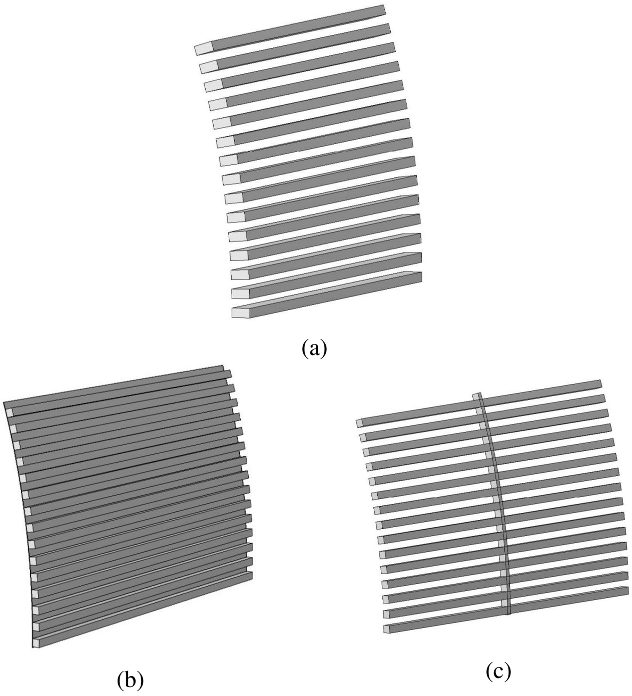


Fig. 8: Three selected designs: (a) elongated pole-piece, (b) bridged pole-piece and (c) ribbed pole-piece.

moment of inertia, makes the pole-piece stiffer, and thus reduces the deflection under load.

Figure 9 shows how maximum deflection changes with respect to the pole-piece height. It can be seen that the radial deflection reduces drastically after apeak at 45 mm pole-piece height, where the 1st natural frequency coincides with the 83 Hz frequency component of the electromagnetic force. However, both the radial and tangential deflections are still high even if the height reaches above 70 mm.

As a consequence of thicker pole-pieces, the torque decreases relatively fast as well because of larger leakage flux. As can be seen from Figure 10, the torque drops from 9.5 MNm to only 7.7 MNm when the pole-piece height is increased to 75 mm.

*2) Bridged pole-piece:* In the second selected design the pole-pieces are attached to each other with a very thin “bridge” made of the same material as the pole-pieces. This reduces the individual deflection by connectiong the pole-pieces to each other and making the pole-piece rotor a hollow cylinder instead of an array of thin beams. This topology is also used frequently in literature [9].

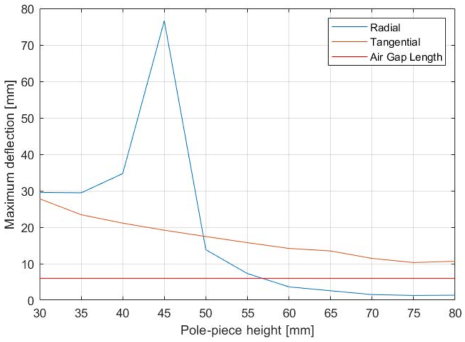


Fig. 9: Maximum radial deflection of the pole-pieces versus pole-piece height.

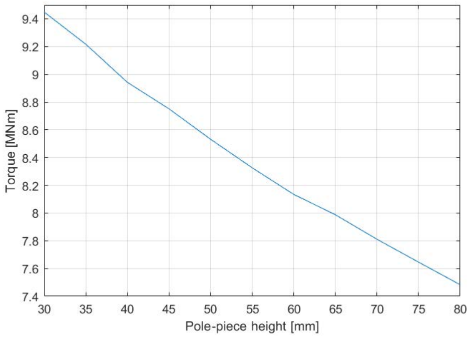


Fig. 10: Torque versus pole-piece height.

The bridged design shows great mechanical improvement compared to the elongated pole-piece design. Even with a bridge of only 2 mm, the deflection can be reduced to 1 mm, as shown in Figure 11.

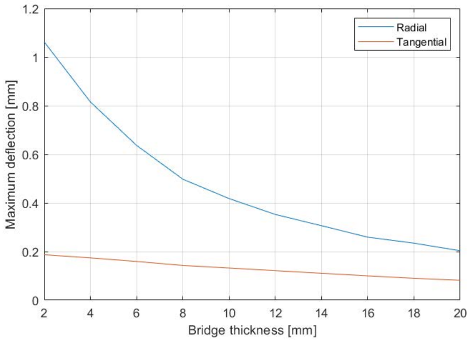


Fig. 11: Maximum radial deflection of the pole-pieces versus bridge thickness, when the pole-piece thickness is 30 mm.

However, looking at Figure 12, it can be seen the torque decreases faster than the case with the elongated pole-pieces.

To limit the deflection within 1 mm, a 2.5 mm bridge is needed, which reduces the torque by 17% already. This is because the bridge allow magnetic flux to “short” between the high-speed rotor poles instead of linking with the stator magnet array or coils.

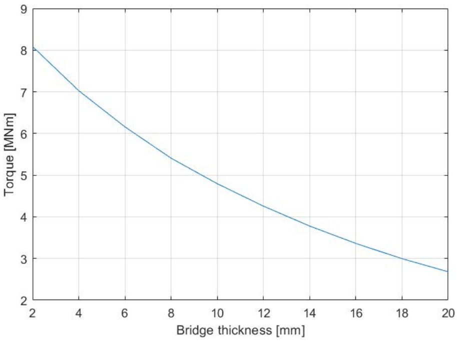


Fig. 12: Torque versus bridge thickness.

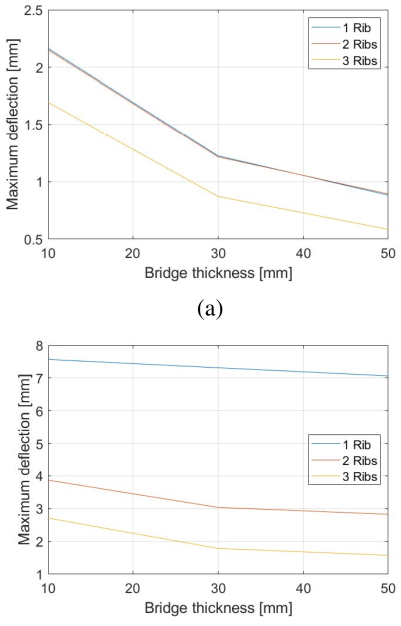
*3) Ribbed pole-piece:* One way to cope with the flux leakage problem is to only have a bridge at specific locations along the length of the pole-pieces, as shown in Figure 8c. This ribbed structure is a trade-off between the rotor stiffness and flux leakage. It can be seen that having an odd number of ribs is preferable over an even number. With an odd number of ribs, there is always one in the middle of the pole-pieces, where the potential deflection is the highest. In this way the most vulnerable point is reinforced.

The results are shown in Figure 13. It can be seen that the tangential deflection depends mostly on the number of ribs rather than their width. Combining the results, it shows 3 ribs of about 27 mm wide can limit the deflection of the pole-pieces below 1 mm.

Since the ribbed pole-piece rotor is a three-dimensional (3D) model, rather than an extruded 2D model like the first two designs, and the electromagnetic FEA model is 2D, the flux leakage caused by the ribs could not be included in the analysis. However, flux leakage of this case can be suppressed by adding ducts at the ribs or using non-magnetic material for the ribs.

TABLE III: Overview of Improvements and Their Impacts on Torque Density

| Model | Deflection | Modification | Torque reduction |
|---|---|---|---|
| Elongated | 1.3 mm | 75 mm high pole-pieces | 19% |
| Bridged | 1 mm | 2.5 mm thick bridges | 17% |
| Ribbed | 1 mm | 3 ribs, 27 mm width | - |



(a)

(b)

Fig. 13: Maximum deflection of the pole-pieces versus rib thickness and for different number of ribs: (a) radial deflection, (b) tangential deflection.

## V. CONCLUSIONS

This paper analyses the mechanical dynamics of the pole-piece rotor of a PDD wind turbine generator, which was previously optimized electromagnetically in the INNWIND.EU project. A 2D electromagnetic model and a 3D structural mechanical model have been made based on available parameters. One way coupling from electromagnetic force to the structural dynamics is implemented. It shows that the deflection of the pole-pieces could go up as high as 5 times as the air gap length, due to very high electromagnetic force and the main force frequency component is close to the natural frequency.

Three different modifications are selected to improve the rotor mechanical performance:

- Elongate the pole-pieces in the radial direction to increase the bending stiffness;
- Connect all the pole-pieces with a thin bridge to create a rigid cylindrical rotor;
- Connect the rotor pieces at a few spots in order to reduce the flux leakage compared to the second modification.

The first model reduces the deflection down to 1.3 mm at the price of a 19% torque reduction. The second model reaches a maximum deflection of only 1 mm with a 17% reduction in torque. The 3rd modification is very promising considering the possibility to reduce flux leakage. However, the exact electromagnetic performance is not able to simulated with the 2D model used in this paper because of its 3D structure.

Only one-way coupling is used in the paper, the electromagnetic damping on the deflection is not considered. The deflection results obtained from the models are not accurate. However, it shows that the electromechanical dynamics of the rotor should be considered in the design of the PDD wind turbine generator and there are potential solutions to suppress the deflections.

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