# **CHAPTER 6**

# **CONCLUSIONS AND FUTURE WORK**

## Conclusions

With the increased capacities and interconnected electrical networks of wind turbines worldwide, reliability, fault-tolerance and modularity terms have gained importance. As a results of this, wind power plants have become inevitable parts of grids even in failure times. Main motivation of this thesis work is to design modular direct drive axial-flux permanent magnet (AFPM) generator for wind turbine applications due to its higher energy yield, higher torque density and volume advantages.

In first chapter of this thesis study, general overview of wind energy harvesting trends and statistics are presented for both in Turkey and worldwide. It’s concluded that worldwide trend is going through power output of 10 MW and above in the near future. Moreover, conventional wind turbine practices are changed from fixed speed, low power systems to high power per turbine, reliable and grid-supportive systems.

In Chapter 2, we mainly focused on wind energy conversion systems. For this purpose first, fundamental equations of wind power harvesting are defined and presented. Then, common challenges of the wind power conversion systems are investigated. According to statistics and literature, main reasons of longest downtimes and failures of wind turbines are gearbox and drivetrain failures. Main disadvantage of direct drive systems are larger outer diameters and mass in order to achieve higher torque values under same power levels. After these findings, existing wind energy conversion technologies and various wind turbine generator concepts are investigated in the literature. Among these generator types doubly-fed induction generators are very popular due to its lower price and experience in both in field and production. However, this type of generator suffers from their partial scale converters and gearbox. Direct drive permanent magnet synchronous generators (PMSG-DD) are found more reliable and feasible solution in terms of efficiency, reliability and fault-ride-through capability. Thus, direct drive PMSG is chosen for the proposed design in this study. Axial flux orientation is selected and implemented in this thesis study because of its torque per volume and axial length advantages. Detailed overview of selected topology was given in related sections. For the final part of this chapter, effects of modularity in modern WECs are discussed and modular concept is chosen, considering the increased importance of modularity and reliability under LVRT conditions.

In the third chapter, analytical design calculations of the proposed AFPM generator and its 50 kW sample FEA verifications are mentioned. For this purpose, detailed mechanical and electromagnetic design equations are described and related drawings are given. In the proposed model outer rotor and C-core configurations are selected. Moreover, magnetic circuit including leakage flux paths are presented and related equations are defined. In the proposed design, power factor is assumed as unity due to selected vector control in the power electronics stage, which is out of scope of this thesis. Structural deflection between C-core limbs due to strong magnetic forces, is also modelled in this thesis. Thermal calculations are based on temperature reference under predetermined current density value according to literature. Eddy losses are calculated for both magnets and windings. Active and structural mass calculations are again presented in this chapter. Finally in this chapter, a sample 50 kW AFPM generator is optimized and design accuracy is tested via FEA. Air gap flux density and induced emf values are chosen for error comparison. According to low error values between analytical and FEA results, design methodology is considered as a verified method for the proposed AFPM generator.

Fourth chapter mainly describes the optimization procedure and optimized parameters of the 5MW 12 rpm AFPM generator. Proposed design method followed in this thesis can be described as a cost optimization procedure which is based on analytical design equations presented previously and wind speed time probabilistic for a given site. In order to achieve more realistic optimization conditions and more realistic design results, real field based wind speed distributions (taken from a WPP located in Çanakkale/TURKEY) are used in the optimization method. A real commercial Gamesa wind turbine power production conditions are referenced in this optimization study. Optimum 5 MW 12 rpm AFPM design parameters are found by implementing the proposed method in MATLAB GA toolbox. In this optimization procedure, energy production income according to real wind probabilistic are taken into account. In addition, penalty constraints and phase voltage levels are selected according to real life requirements. Optimization algorithm evaluates the candidate individual current density values and adjust this in order to continue process. Details of the algorithm and performance parameters of the optimum generator is given in this chapter.

10 mm air gap value is selected according to pre-limited stator outer diameter and machine design practices. Seven different penalty functions are employed in order to search for a better optimization result and convert our constrained optimization problem to an unconstrained optimization problem. According to optimized generator performance results, the most dominant mass component of the generator is the structural mass by 61% while its mass is cost is less dominant. In addition PM cost is the most dominant compound of the cost of the generator while it is the least dominant mass component. This can be considered as a disadvantage of the design, as it was predicted before. Therefore, it can be inferred that, optimization algorithm tried minimize the amount of PM used, for the sake of a cheaper solution. Resultant generator has a large outer diameter due to its direct drive nature but very advantageous in axial length aspect. This length advantage is used by the optimization and the optimum design is determined as six-parallel axially stacked AFPM generators, which gives modular ability and huge advantage in terms of transportation, installation and repair costs. Optimized generator has an efficiency of 95.4%.

In the fifth chapter, FEA verification of the proposed 5MW 12 rpm AFPM generator was the main motivation. For this purpose, a parametric model based on the optimized analytical design results is created in Maxwell 3D environment. Air gap flux density and phase voltages are investigated by using magnetostatic and transient analyses. According to these simulation results, it’s concluded that air gap flux density and phase voltages are predicted by the error rates of under 5% and 1%, respectively. Also in this chapter coefficient of eddy loss, which acts on magnets, is estimated as 18 kW/m3. At the end of the Chapter-5, mass and power level comparison is made between our proposed generator with other commercial generators. It’s concluded that when compared with other counterparts, proposed generator has reasonable and preferable power and mass ratings among them, considering the modularity and reliability advantages.

To sum up, a modular direct drive AFPM generator is analytically designed, optimized under realistic conditions and verified by FEA in this thesis study. This topology is selected due to its higher energy yield, higher efficiency, reliability and axial length advantages. Direct drive allows generator to operate more efficient due to eliminated gearbox. However large outer diameter, which is optimized as 10 meters in this design, and highly magnet price dependent overall cost are the biggest challenges for the proposed design.

## Future Work

Several points can be considered in order to improve the proposed AFPM generator in this study:

* **Detailed Thermal Network:** In this study, optimization is forced to higher efficiency values because of simple thermal approach followed during the design. However, more detailed thermal network of the generator can be studied for a more realistic design optimization. In addition, thermal flow analysis can be implemented for the design.
* **FEA integrated optimization:** Optimization and FEA verification stages are separated in this study. Therefore, any mistake belong to optimization procedure could be understood at the final stage, which makes overall procedure longer and inefficient. Instead, Maxwell and MATLAB environments can be linked together for the integrated optimization-FEA processes.
* **Prototype testing:** Like the most of the real machine design procedures, low-scale prototype production and testing in a real life conditions after the FEA verification can result in better designed generators in terms of electromechanical and thermal means.