# **CHAPTER 5**

# **FEA VERIFICATION**

## Introduction

In the previous chapter, optimization procedure of the proposed AFPM generator was described and required design parameters were determined and presented by using genetic algorithm optimization. As a principle in electrical machine design, it is important to verify the design in terms of electromagnetic and electrical performance before the production [1], [2]. For this purpose, modern analysis techniques and computer programs are used. In this chapter, design parameters of the optimized generator will be used in the 3D FEA modelling and analysis in order to verify the electromagnetic and electrical performance of the proposed AFPM generator. ANSYS Maxwell® is employed during the 3D finite element analyses. Analysis configurations of the magnetostatic, no-load transient and full load transient simulations will be presented in the following subsections. As mentioned in Chapter-3, air gap flux density and no-load induced emf values are investigated during the analyses. In addition, full load analysis of the proposed AFPM generator is made in order to calculate the coefficient of eddy losses acting on the permanent magnets. Related graphs and simulation results will be given in the following subsections. At the end of the chapter, comparison of the optimization results of analytical design and the 3D FEA analysis will be given for the proposed AFPM generator with related error rates. Another comparison will be made between commercial MW level wind turbines and the proposed AFPM wind turbine generator.

## Magnetostatic Analysis

In the finite element computation environment, magnetostatic analyses are done in order to estimate the electromagnetic behaviour of the electromechanical systems under static conditions, i.e. no-motion. For our study, magnetostatic analysis is applied to proposed generator model in order to calculate air gap flux density and flux path in the machine. Before these verifications, ANSYS Maxwell magnetostatic FEA configuration setup will be presented.

## Magnetostatic FEA Configurations

In the modelling stage of the generator in ANSYS Maxwell, 1/54 symmetrical model is employed. Therefore excessive mesh computation and analysis time can be saved. In Fig. 5-1, mesh plot of the magnetostatic model is given.

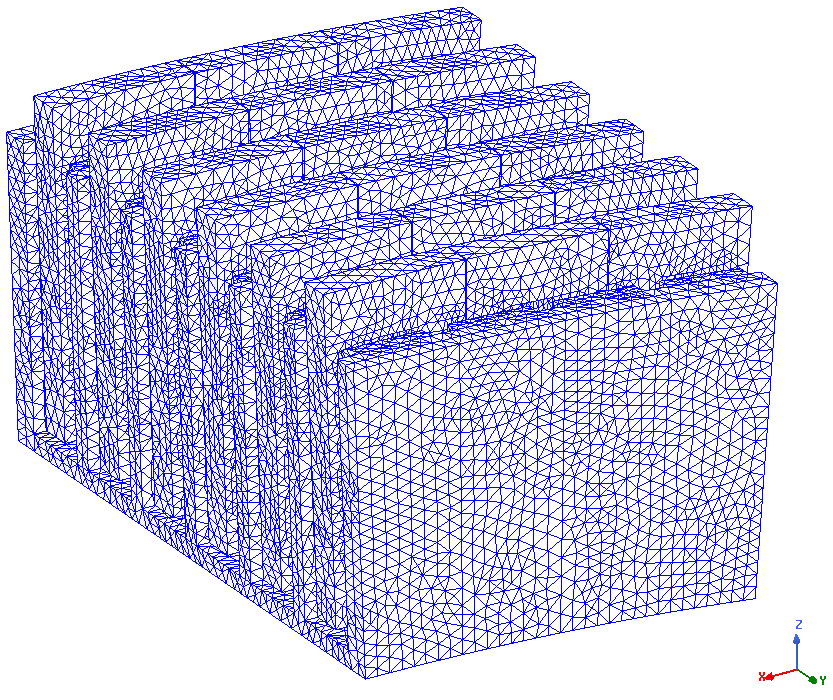


Fig. 5-1. Magnetostatic model mesh plot

Magnetostatic analysis setup configurations and mesh size configurations are given in Table 5-1.

Table 5-1. Magnetostatic FEA Configurations

|  |  |
| --- | --- |
| **Property** | **Value** |
| Mesh size | 25 mm |
| Percent error | 0.5 |
| Maximum number of passes | 15 |
| Refinement Per Pass | 30% |

## Air gap Flux Density verification

In this section, air gap flux density value of the proposed generator is investigated and compared with the analytically calculated air gap flux density value in order to verify the proposed 5MW 12 rpm design. In Fig. 5-2, air gap flux density values with respect to position in the air gap between magnets are depicted.

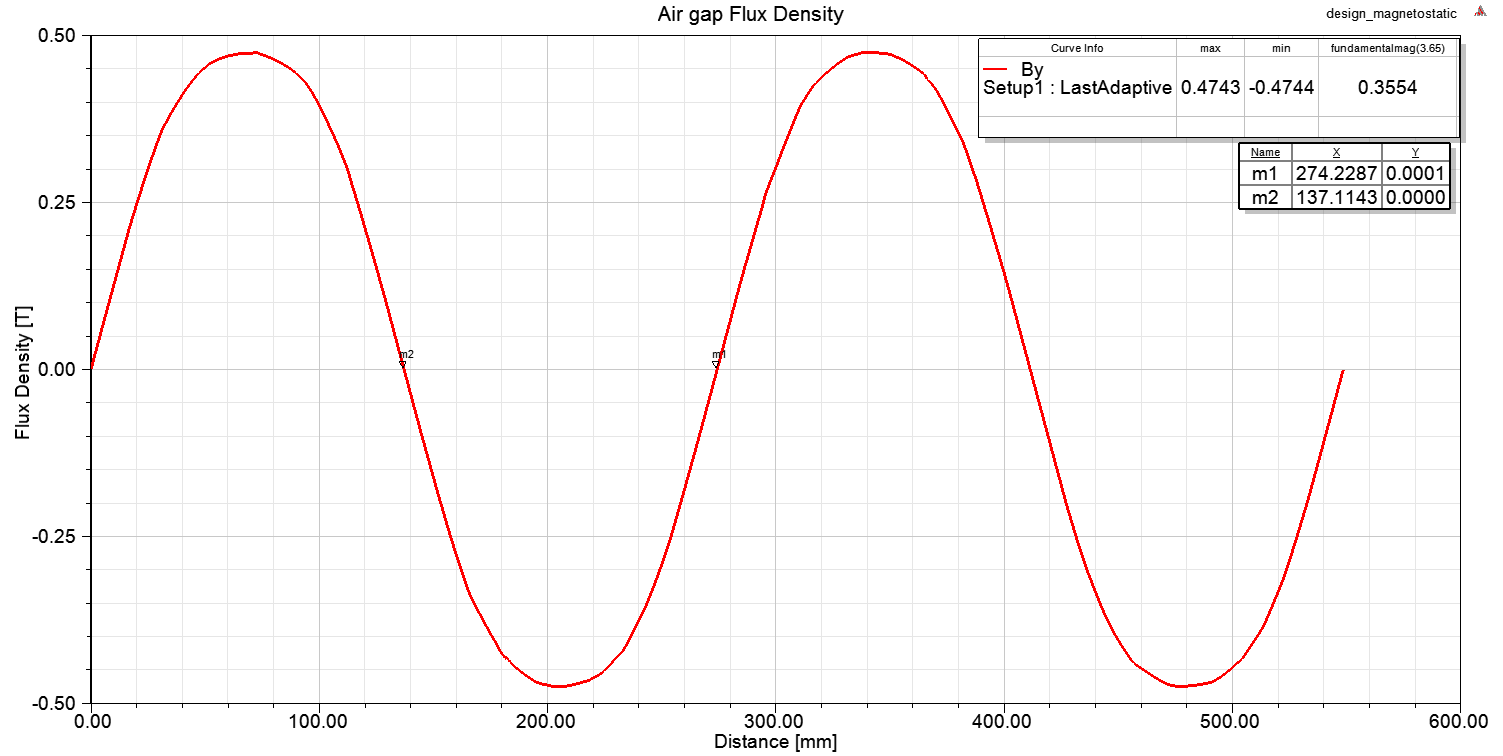


Fig. 5-2. Proposed design air gap flux density graph from FEA

According to these FEA results, air gap flux density characteristics of the proposed design and comparison with analytical calculation results are summarized in Table 5-2. In Fig. 5-3, variation of the air gap flux density together with analytical and FEA results are shown. Black labeled flux density is the calculated flux density value with a flat-top value of 0.459 T while red and blue labels show the analytically calculated fundamental harmonic peak air gap flux density and FEA results, respectively.

Table 5-2. Comparison of the analytical and FEA results for the air gap flux density

|  |  |  |  |
| --- | --- | --- | --- |
| **Property** | **FEA Value (T)** | **Analytical Value (T)** | **Error** |
| Air gap flux density -peak | 0.474 | 0.459 (flat-top) | 3.1% |
| Air gap flux density fundamental-peak | 0.502 | 0.516 | 2.7% |

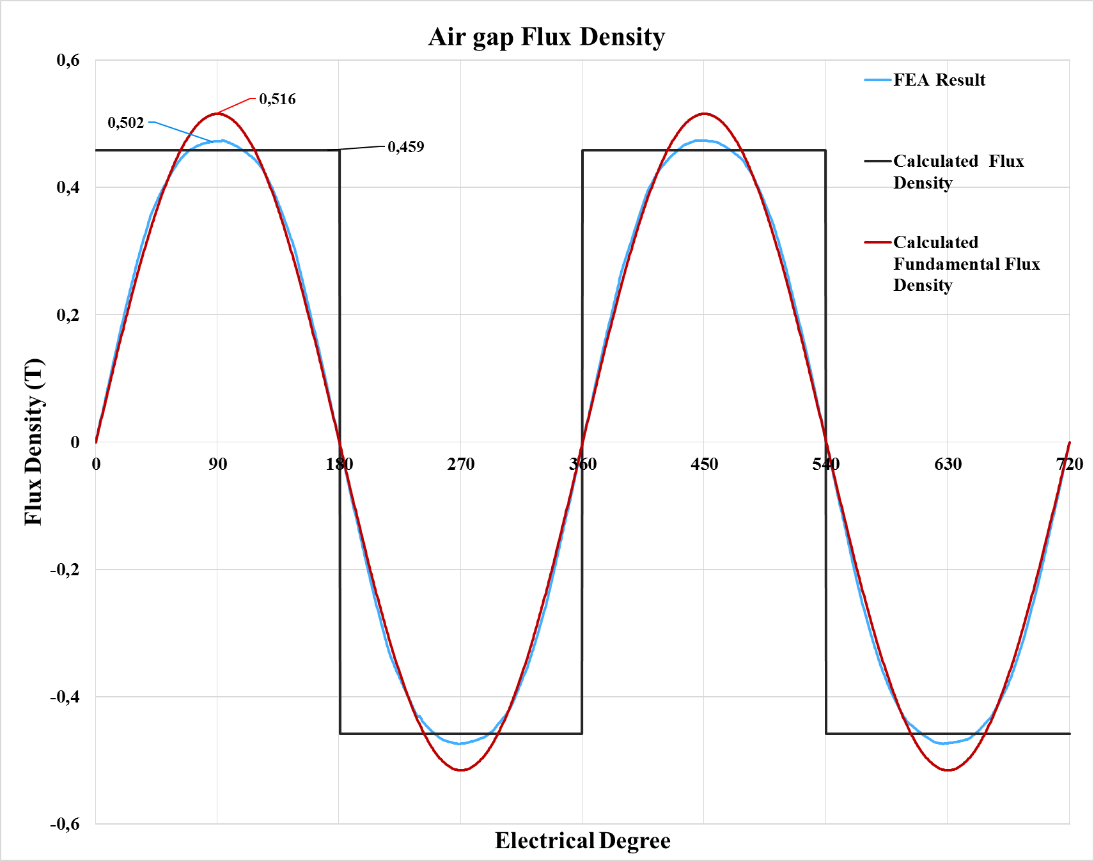


Fig. 5-3. Airgap flux density graph with analytical results for the 5 MW design.

As mentioned in previous chapters, air gap flux density value is a critical value that has to be verified before the production stage of the electrical machine. It can be seen from the Table 5-2 and Fig.5-3 that analytically calculated values and finite element analysis results of the air gap flux density of proposed AFPM generator are in good agreement and related error values are reasonable. Small difference between FEA results and analytically calculated flux density is due to leakage fluxes that can not be calculated by the analytical method in this study. In Fig. 5-4, top view of the flux density vectors is shown around the poles and air gaps. In Fig. 5-5, flux density distribution over the steel core parts is shown.



Fig. 5-4. Airgap flux density vectors for the 5 MW design.

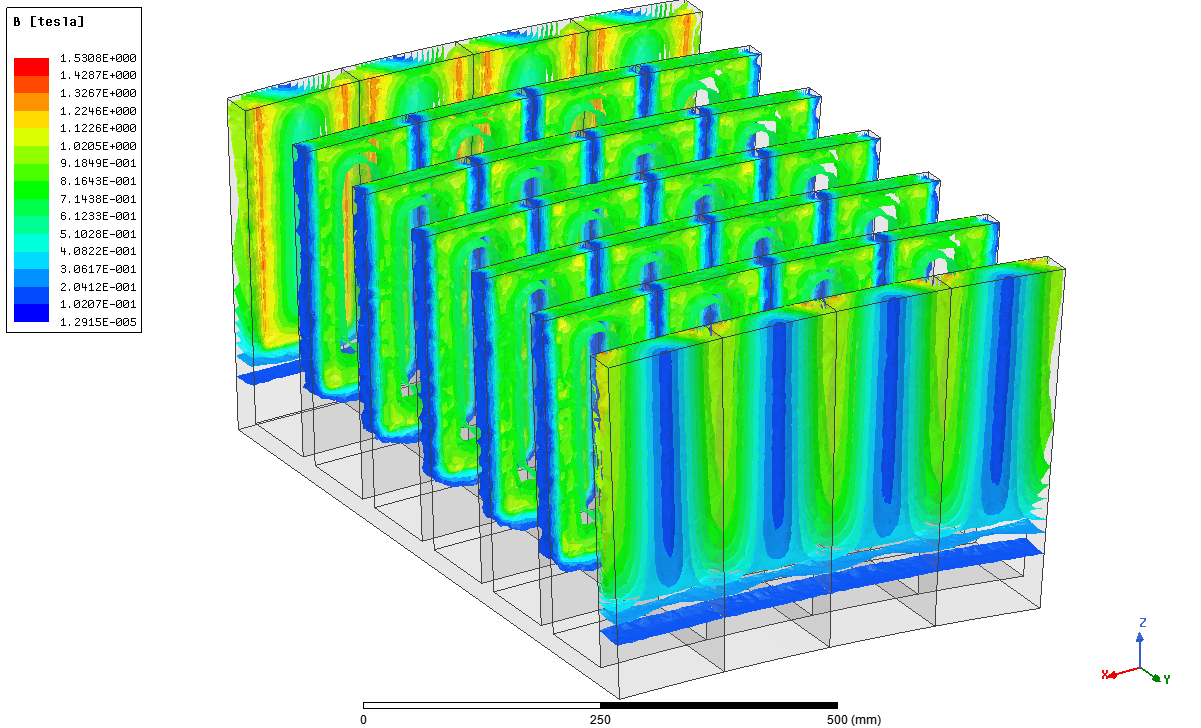


Fig. 5-5. Flux density distribution over the steel cores of the proposed 5MW design.

## Transient Analysis

In the transient finite element environment, analyses are done in order to estimate the electromagnetic behaviors of the electromechanical systems under dynamic conditions, i.e. moving. Three main objectives are followed in terms of transient FEA in this thesis. These are; no-load induced emf, full-load phase voltage and full-load eddy current coefficient estimation. In the following subsections, these objectives will be described and related verifications of the proposed AFPM generator will be presented. Before these verifications, ANSYS Maxwell transient FEA configuration setup will be presented.

## Transient FEA Configurations

In the transient model, two different mesh sizes are used in order to avoid computational burden of simulation. 1/54 symmetrical model is employed again in order to avoid computational burden. Configurations of the transient FEA is given below in Table 5-3.

Table 5-3. Transient FEA Configurations

|  |  |
| --- | --- |
| **Property** | **Value** |
| Mesh size (no-load) | 25 mm |
| Mesh size (full-load) | 30 mm |
| Time step | 1 ms |
| Stop time | 0.1 s |
| Speed | 12 rpm (rated) |

## No-load Model

In this section, only induced emf of the proposed AFPM generator will be investigated under no-load conditions. For this purpose, zero current value is assigned to three phase windings together with infinitely high resistance values.

## Induced emf verification

If we recall the circuit diagram given with Fig. 3-12 in Chapter-3, induced emf  corresponds to the voltage measured across open phase windings when no current flows through and machine rotates at rated speed of 12 rpm. In Fig. 5-6, circuit diagram of the machine is given and induced emf is indicated with red circle. In Fig. 5-7, induced emf graph from the finite element analysis is given. According to this figure, induced emf per phase rms value is measured as 394.5 V.

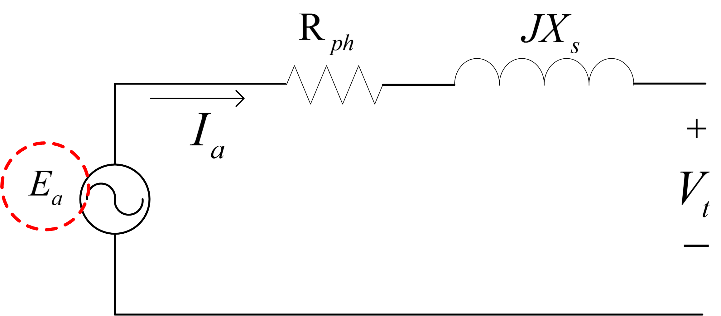


Fig. 5-6. FEA induced emf () measurement equivalent circuit

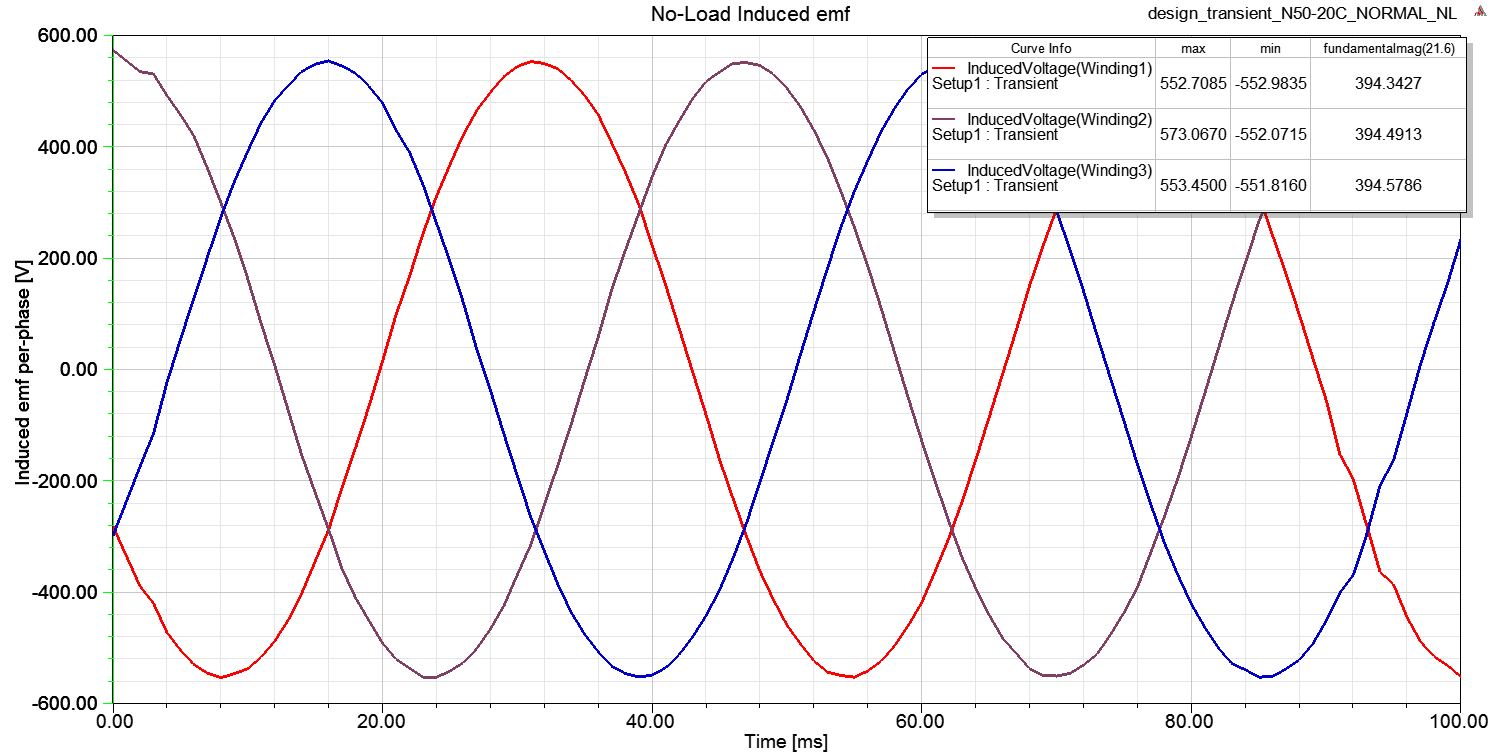


Fig. 5-7. Proposed design induced emf per phase results from FEA

Comparison of the analytically calculated results with FEA results for the induced emf per phase is given in Table 5-4 below. As it can be seen from this table, error rate is very low. Therefore, analytical design method is verified with FEA in terms of induced emf values.

Table 5-4. Comparison of the analytical and FEA results for the induced emf per-phase

|  |  |  |  |
| --- | --- | --- | --- |
| **Property** | **FEA Value (V)** | **Analytical Value (V)** | **Error** |
| Induced emf per-phase rms | 394.5 | 395.6 | 0.27% |

## Full-load Model

In this section, phase voltages and value of the magnet eddy loss coefficient will be investigated under full-load conditions and related verifications will be presented. For this purpose, three phase windings of the proposed AFPM generator are excited by using rms phase current value which was determined in the previous chapter. During the excitation, load angle which was determined in the previous chapter is added to these excitation equations in order to achieve “in phase” current and voltage waveforms, i.e. unity power factor as it is assumed in this thesis study.

## Phase Voltage verification

As mentioned in the previous subsection, phase windings are excited so that current and voltage waveforms are in phase and unity power factor condition is obtained. This condition is shown in Fig.5-8.

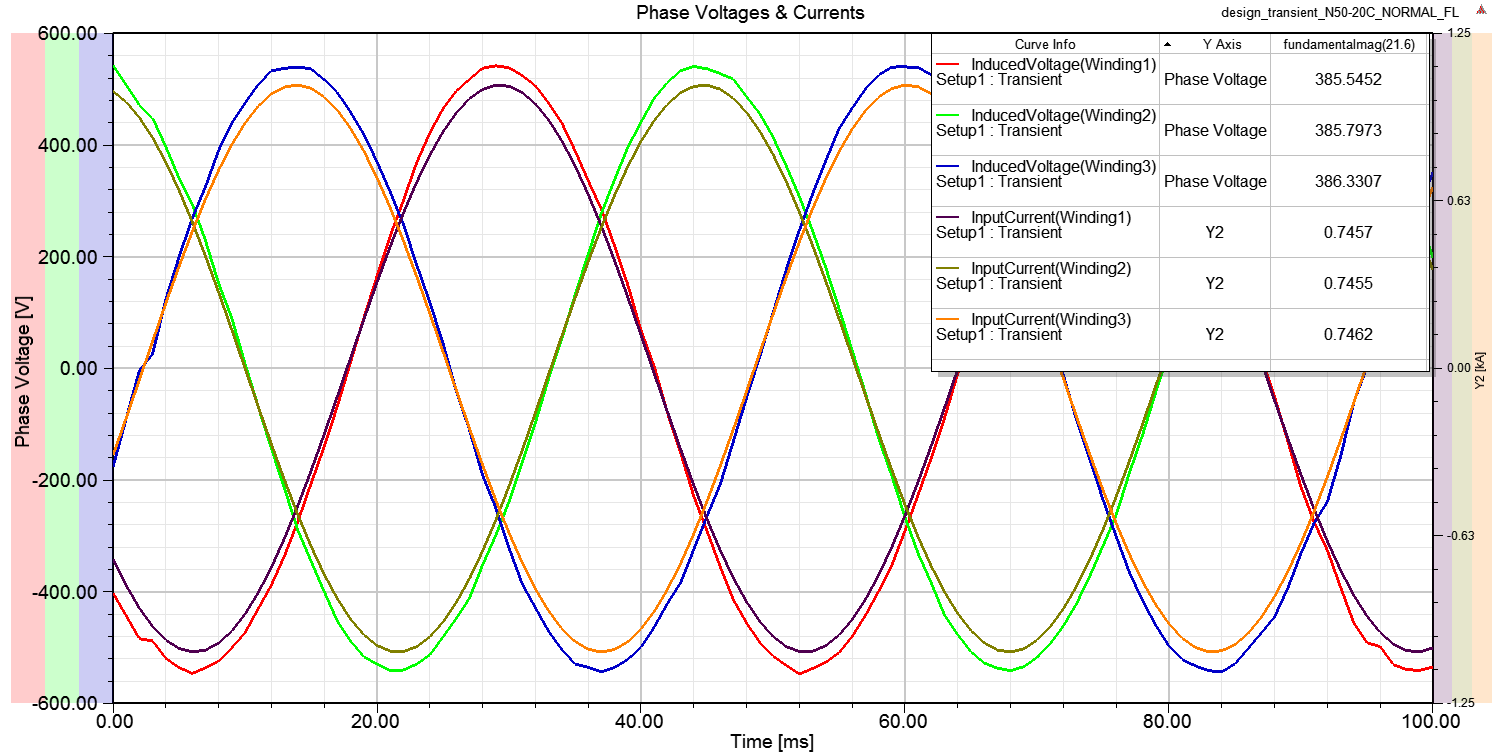


Fig. 5-8. Proposed design full-load phase voltages and currents

Although in Chapter-3 phase resistance is omitted when drawing the approximately equivalent circuit and related phasor diagrams, in analytical calculations of this thesis study phase resistance values are taken into account. Therefore, equivalent circuit given in Fig. 5-6 is used when calculating the phase voltage of the proposed AFPM generator. According to this equivalent circuit, phasor diagram of the proposed design and phase (terminal) voltage equation are given in Fig. 5-9 and Eq. 5-1, respectively.

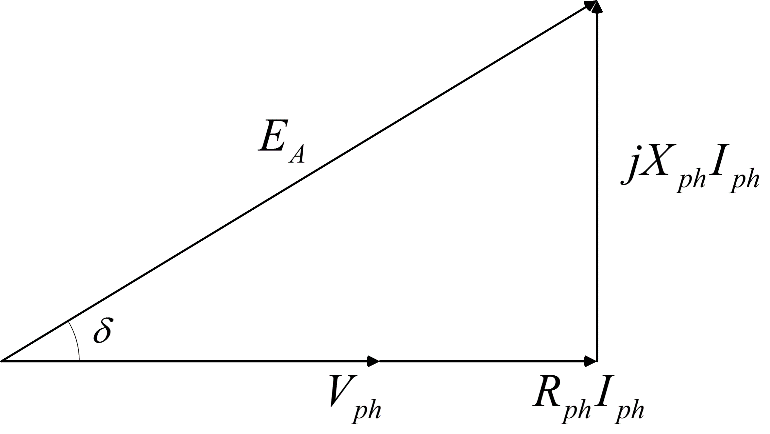


Fig. 5-9. Proposed design phasor diagram including resistance

 (5-1)

However, Maxwell FEA does not include the resistance into calculation. Therefore, resistive voltage drop should be subtracted from the rms phase voltage value calculated by FEA. This resistive voltage drop can be easily calculated by using the phase resistance () value which was determined in the previous chapter. Phase reactance  of the FEA can be found by adjusting the analytically calculated reactance value as follows,

 (5-2)

Phase inductance value from FEA  is measured as 1.04 mH while analytical design method calculated it as 0.82 mH. Therefore, phase reactance of the FEA can be estimated as follows,

 (5-3)

As it can be seen from the Fig. 5-8, rms phase voltage without resistive drop is measured as 385.6 V from FEA. Resulting phase voltage obtained by FEA is calculated according to Eq. (5-1) as follows,

) (5-4)



Comparison of the analytically calculated results with FEA results for the phase voltage is given in Table 5-5 below. As it can be seen from this table, error rate is very low. Therefore, analytical design method is verified with FEA in terms of phase voltage values.

Table 5-5. Comparison of the analytical and FEA results for the phase voltage

|  |  |  |  |
| --- | --- | --- | --- |
| **Property** | **FEA Value (V)** | **Analytical Value (V)** | **Error** |
| Phase voltage | 371.2 | 371.3 | 0.02% |

## Eddy loss coefficient estimation

In analytical calculations part of our proposed design method, eddy current losses acting on the magnets are taken into account. For this calculation, a coefficient of this loss per unit volume of the magnet is estimated by using FEA simulations.

Eddy losses are result from the ohmic losses of the magnet due to induced currents on them. Following equations are employed during the generation of FEA calculation for eddy losses for one unit of PM,





 (5-5)

FEA integrates the expression above in one whole PM volume. Resulting eddy loss coefficient for per unit volume of PM is calculated as 18 kW/m3 . In Fig. 5-10, aforementioned eddy current density vectors on one PM block is depicted.

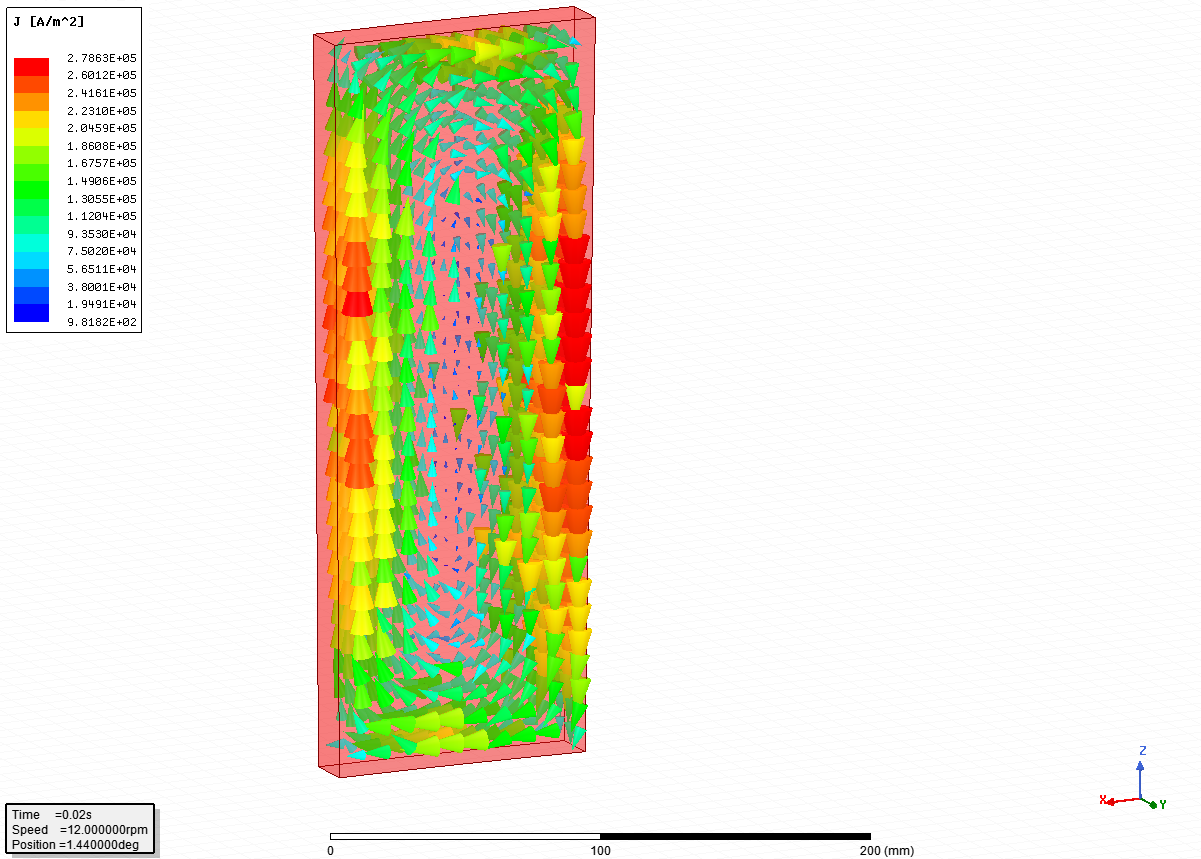


Fig. 5-9. Eddy current density vectors on magnet block

## Proposed model comparison

In this section, proposed and verified AFPM generator will be compared with other commercial MW-level wind turbine generator systems in terms of power and mass aspects. Since unreasonable conditions may be encountered when comparing different drivetrain configurations, mainly low-speed direct drive topologies are compared in this section. Although they are not fully direct drive (two stage gearbox), few topologies are selected for the comparison due to their similar power level just as our proposed generator. Therefore, this section is based on power and mass comparison of the selected commercial products, respectively.

## Power Considerations

In this section, 11 different commercial wind turbine generators are compared with proposed AFPM generator according to their power levels. In the selection stage of these comparable turbine generators, it is intended to select generators from similar power levels to proposed design. Comparison is tabulated in Fig. 5-11. As it can be seen from this table, proposed AFPM generator has reasonable output power level according to its modern counterparts. Moreover, total output power of the proposed design can be increased by adding axial stack of generators.

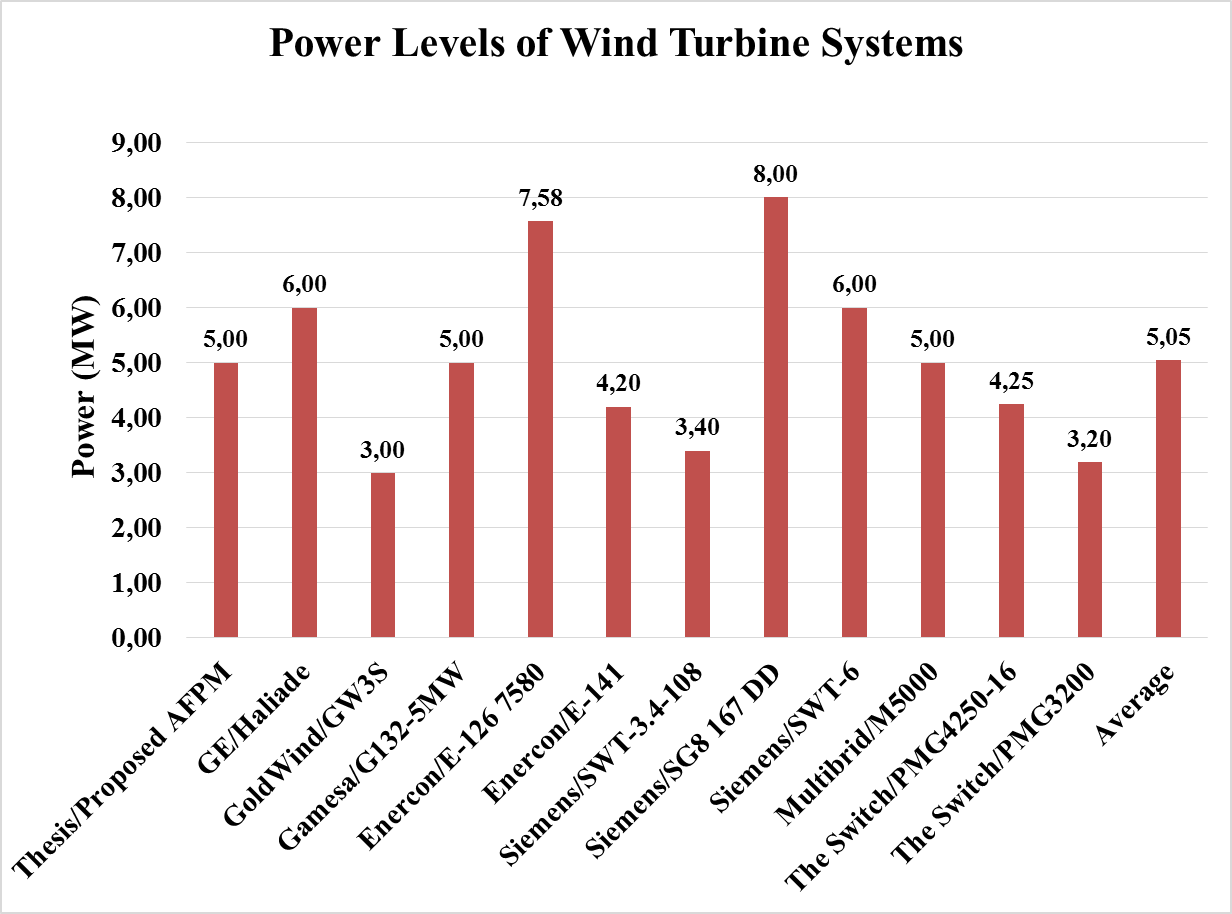


Fig. 5-11. Comparison of proposed design and commercial wind turbine generators in terms of output power

## Mass Considerations

In this section, 5 different commercial wind turbine generators are compared with proposed AFPM generator according to their weight. Since most manufacturers do not share the weight information of their products, fewer commercial wind turbine generators can be compared with our proposed design. However, results of comparison is still reasonable. Because most power levels are similar and these compared commercial products use same generator configuration (DD-PMSG/EESG) except Multibrid and Gamesa products which are 2G-PMSG. Comparison table is given in Fig.5-12. According to this comparison, proposed AFPM configuration can be preferred by the market especially when modular construction taken into account. Large structural mass results in larger total mass when compared with other generators. However, modular design of the proposed generator allow easier and cheaper transportation, installation and repair conditions thanks to its lighter total mass per axially-stacked machine configuration.

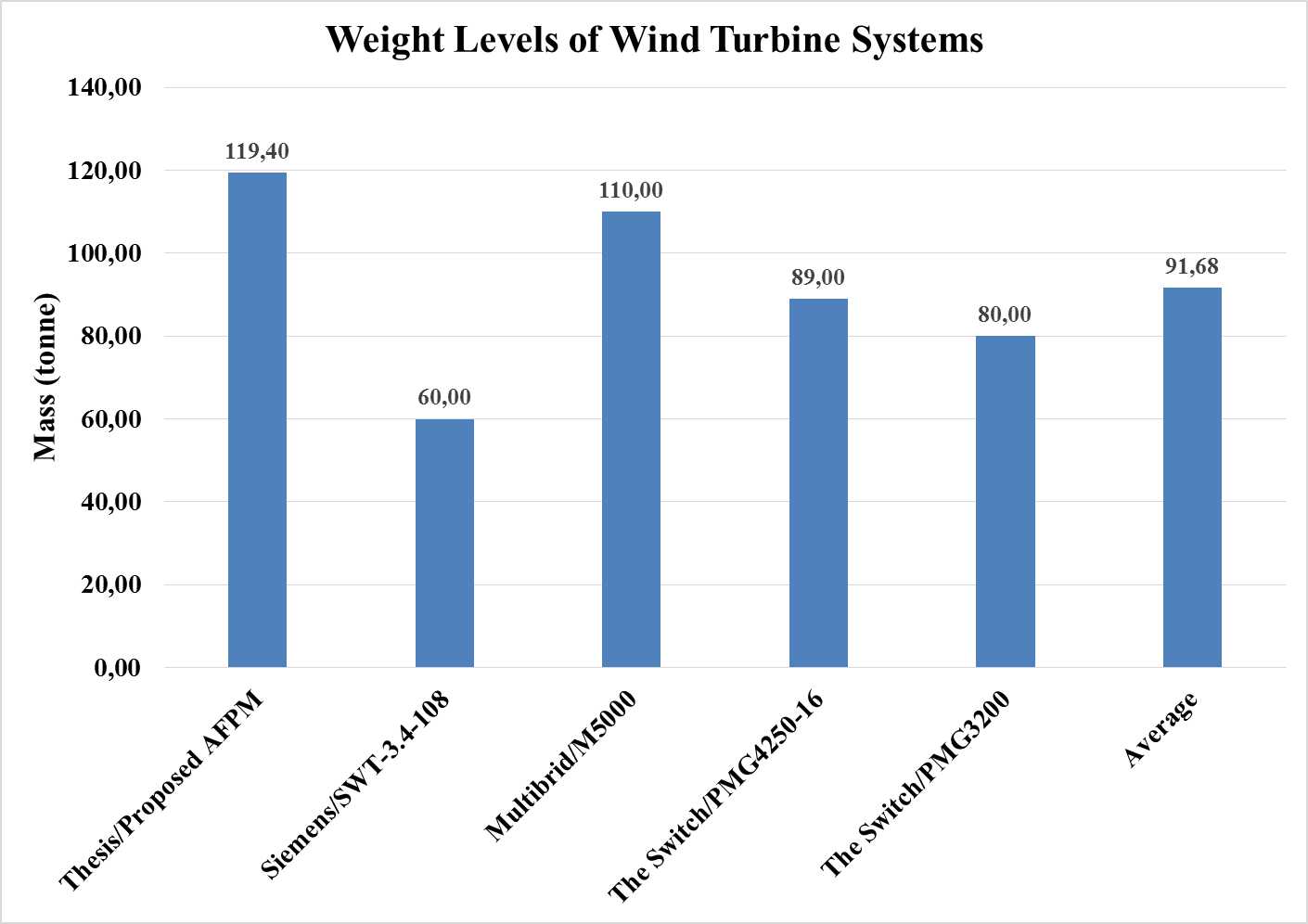


Fig. 5-12. Comparison of proposed design and commercial wind turbine generators in terms of weight

## Conclusion

In this chapter, FEA verification is made for the proposed AFPM generator. For this purpose, analytical design parameters, which were calculated in the previous chapters, of the proposed generator are used to model and analyse the performance of AFPM in Maxwell 3D environment. Magnetostatic and transient analyses are performed for air gap flux density and phase voltage values. According to results, proposed analytical design model is verified in terms of FEA. Error rates are very small between analytically calculated values and finite element measurement results. In addition, coefficient of eddy loss acting on the magnets is estimated by using full load simulations. Related comparison tables and FEA drawings are given in previous sections. In the final part of this chapter, comparison of proposed and verified generator with commercial wind turbine generator counterparts. Mostly, similar power level and same generator topologies are chosen. According to comparison tables of the generators, proposed AFPM can be preferred both in power level requirement and mass conditions. Main reason of this selection is result from axial and modular configuration of the proposed generator.

**References**

[1] N. Rostami, M. R. Feyzi, J. Pyrhonen, A. Parviainen, and V. Behjat, “Genetic Algorithm Approach for Improved Design of a Variable Speed Axial-Flux Permanent-Magnet Synchronous Generator,” *IEEE Trans. Magn.*, vol. 48, no. 12, pp. 4860–4865, 2012.

[2] J. F. Gieras, R.-J. Wang, and M. J. Kamper, *Axial Flux Permanent Magnet Brushless Machines*, vol. 3 ed. Dordrecht: Springer Netherlands, 2008.