# **CHAPTER 3**

# **DESIGN OF PROPOSED GENERATOR**

In previous chapters, background about wind energy conversion systems and detailed overview of most used generator types are given. Then, challenges of modern wind turbine systems and fundamental equations are discussed. In chapter 2, direct drive axial flux permanent magnet generator is chosen for design in this thesis study because of its lower mechanical losses due to eliminated gearbox, high torque per volume and axial length advantages thanks to selected axial flux permanent magnet synchronous machine topology. In this chapter, electrical and mechanical design parameters of axial flux permanent magnet generator will be described. To do this, analytical design equations of proposed generator are given in the following sub-sections. These design equations will be used in following chapters for genetic algorithm optimization and electromagnetic design. Finally, a comparison of electromagnetic FEA and analytical calculation for given dimensions of proposed generator will be given to ensure the accuracy of the finite element analysis technique.

## Mechanical and Electrical Parameters

In previous chapter, it’s decided to use axial flux permanent magnet synchronous machine. In this machine, inner air-cored stator and outer rotor surface mounted permanent magnets will be used. General overview of proposed generator is given in Figure 1. In this figure, three axially stacked generator blocks are given. However, this image includes only 4 poles of proposed system. Permanent magnets are shown with blue and red colors, showing the direction of magnetization. Concentrated windings are shown with green colors. C-shaped steel rotor discs are shown with gray colors.

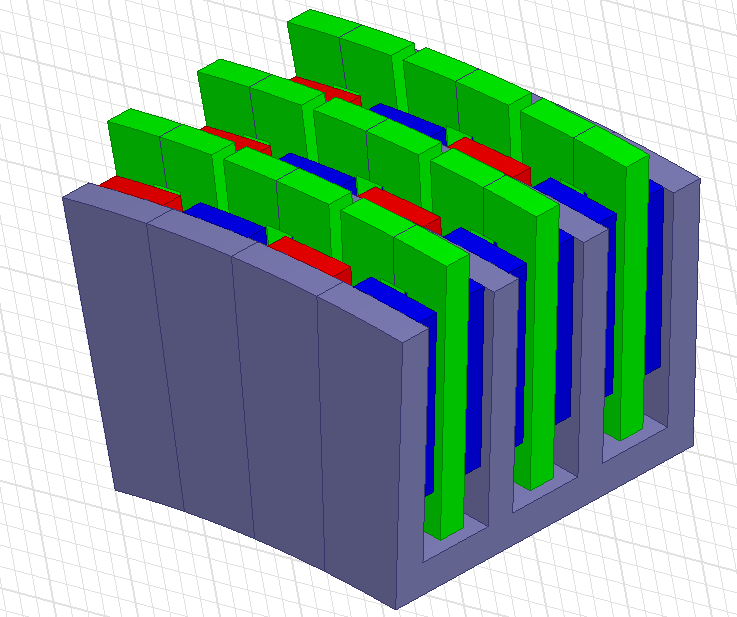


Figure-1. Proposed AFPM generator

## Sizing Equations

Per-phase equivalent circuit and phasor representation of synchronous machine is given Figure 2 and Figure 3, respectively. Output rms phase voltage (terminal voltage) of a typical synchronous machine is calculated as follows,

(1)

Where, *Eph,rms*is the induced emf rms value and *Zph,rms* is the phase impedence under steady state temperature.



Figure-2. Equivalent circuit of the synchronous machine where Ea is the induced emf, Ia is the phase current, Xs is the synchronous reactance and Vt is the phase voltage



Figure 3. Phasor diagram of synchronous machine where δ is the load angle, Φ is the power factor angle

*Eph,rms* is calculated as follow,

(2)

(3)

Where *e* is the induced emf in one turn of conductor, *Nt* is the number of turns, *Ns* is the number of coils in series.

Phase voltage peak and rms values according to Figure-3 are calculated as follows,

 (4)

 (5)

where  and  are phase resistance and phase reactance, respectively. Induced emf in one turn of coil is calculated as follows,

 (6)

where  is the peak flux linkage,  is the pole pitch and *v* is the airgap linear speed. Peak flux linkage is calculated for the proposed generator as follows,

 (7)

Where  is the leakage coefficient, ro and ri are the outer and inner radius of rotor respectively,  and  are the outer and inner length ratios of the coil pitch and width of the winding, respectively, Np is the number of poles. Leakage coefficient  can be taken as constant of 0.95. First harmonic value of the air-gap flux density Bag is given as follows,

(8)

where is the magnet pitch-to-pole pitch ratio and is the flux density in the airgap. Airgap linear speed *v* can be calculated as follows,

 ()

where  is the mean radius and  is the mechanical speed in rad/s. This mechanical speed is calculated as follows,

 ()

where *n* is the rotational speed in rpm. Since proposed machine is a synchronous generator, frequency of the machine is defined as follows,

 ()

## Geometrical parameters

Length ratios  and  given in (5) are calculated as follows,

 (9)

 (10)

 (11)

where is the difference between two distances. Pole pitch  value in (6) can be calculated as follows,

 (12)

Outside radius *ro* and inside radius *r*i are given as follows,

 (13)

 (14)

where  is the mean airgap radius and *l*m is the axial length of the magnet. Magnet pitch-to-pole pitch ratio is also referred as pole shoe arc-to-pole pitch ratio in [1] and can be calculated for our design as follows,

 (15)

This ratio can be taken as variable between 0.65 and 0.85. In our design it’s used as 0.75. Lower values of this variable leads to lower utilization of permanent magnets, hence higher values are preferred. Steel-to-steel distance *lss* can be calculated as follows,

 ()

In this equation *hm* is the height of the magnet, *lmm* is the magnet-to-magnet distance. C-shaped core is given in Figure 4 with related distances. Magnet-to-magnet distance can be calculated as follows,

 ()

where  is the height of the winding and *g* is the airgap clearance.

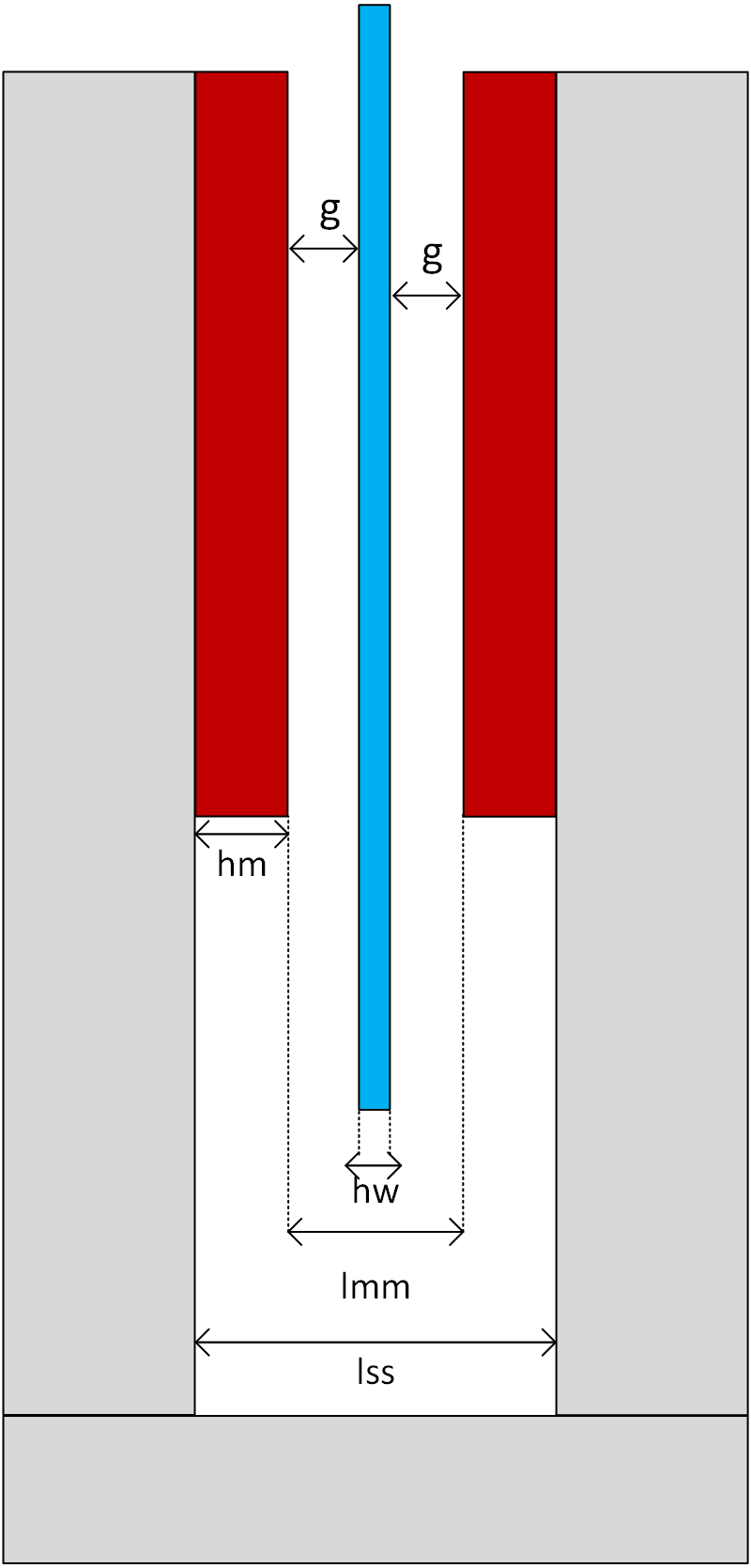


Figure 4. C-shaped core with defined distances. Gray: steel core, Red: Permanent magnets, Blue: stator windings

## Phase turns, phase resistance & inductance and flux densities

Peak and rms values of the total current per phase can be calculated as follows,

 (16)

 (17)

where  and  are peak and rms values of the phase current respectively,  is the current in one coil,  is the number of parallel coils.  value is calculated as follows,

 (18)

where *J* is the current density and  is the cross-sectional area of the conductor. Current density value can be selected before the design process as a constant. Cross-sectional area of the conductor, namely  can be calculated as follows,

 (19)

In this equation  is stand for effective window area of the conductors and calculated as follows,

 (20)

where *hw* is height of the winding, *tw* is the width of the winding and *kfill* is the fill factor for the winding coils. Width of the winding value *tw* is calculated as follows,

 (21)

Coil pitch  which is used in (7) and (19) until now, can be calculated as follows,

 (22)

Ratio of (4/3) used in equation (22) is a natural result of the structure of the selected axial flux PMSG and will be used in related calculation as constant.

Resistance of one coil is calculated as follows,

 (23)

where  is resistivity for copper conductor, *lt* is the mean turn length for a coil and calculated as given in (24).

 (24)

where  ,  and  are end, middle and structural parts of the coil, respectively. These lengths are calculated as follows,

 (25)

 (26)

 (27)

Resistance per phase value is based on resistance per coil and calculated as follows,

 (28)

Resistance value given in (28) was calculated without thermal effects. Resistance value including thermal effects can be calculated as follows.

 (29)

where  is the temperature coefficient of copper and  is the temperature difference between ambient and desired operating temperature. Phase reactance  value is calculated as follows,

 (30)

where  is the angular frequency,  is the inductance of a coil. Angular frequency and inductance of a coil are calculated as follows,

 ()

 () ()

where  is the flux linked by coil, *lss* is the C-core steel-to-steel distance. Phase impedence *Zph* can be calculated using phase resistance and reactance values as follows,

 ()

## Volume and mass Equations

## Losses

Total energy loss in the generator is sum of the core losses and the copper losses.

 ()

Copper losses  are calculated as follows,

 ()

Core losses consist of eddy losses both on coils and magnet surface. These losses are calculates as given below,

 ()

 ()



where ,  are coil and magnet components of eddy loss respectively,  and  are thickness and height of the copper conductor respectively, *Bag* is the airgap flux density without leakage flux assumption, *keddy* is the eddy loss coefficient used in calculating magnet surface eddy loss, *Nc* is the number of coils. These variables are calculated as follows,

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Number of coils per phase (*Nc,ph*) is calculated by dividing *Nc* value by 3. Number of coils in series (*Ns*) is calculated as follows,

 ()

Thickness and height of the copper values are calculated as follows,

 ()

 ()

In the equations above, ,  and  are height of the coil, thickness of the coil and thickness of the insulation material, respectively. These parameters are calculated as follows,

 ()

 ()

where  and  are thickness of epoxy and number of parallel strands in a coil, respectively.

## Power and Efficiency

Total output electrical power of the generator is given as follows,

 (31)

Efficiency of the generator is calculated as follows,

 (32)

**References**

[1] J. F. Gieras and M. Wing, *Permanent Magnet Motor Technology: design and applications*, vol. 113. 2002.

[2] B. S. Guru and H. R. Hiziroglu, “Electric Machinery and Transformers,” *Oxford Univ. Press*, p. 741, 2001.