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RESEARCH REPORT
Electromagnetic Optimization of Direct-drive generators
(Deliverable No.: D 1B2.b.hp2)

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Abstract:
The objectives of this report are:
- assessment of different topologies of permanent magnet (PM) generators for large direct-drive wind turbines
- development of new configurations of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance.

In order to assess different topologies PM generators, a comparative design of different PM generators for 5 MW and 10 MW direct-drive wind turbines is represented in chapter 2, using the analytical models developed in a previous report, D 1B2.b.4. From the overview of different PM machines and the identification of the active mass-competitiveness of those machines in a previous report (Deliverable No.: D 1B2.b.1), a slotted surface-mounted radial flux permanent magnet (RFPM) generator and four different transverse flux permanent magnet (TFPM) generators are selected for the comparative design. These five generators are assessed based on the criteria of active mass, loss, cost, efficiency and force density.

Chapter 3 deals with a new configuration of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance. Among four TFPM generators discussed in chapter 2, the single-sided, single-winding flux-concentrating TFPM generator with U-core (TFPMG-U) is selected as a suitable generator type for large direct-drive wind turbines. The RFPMG is considered as a reference generator in the design. To make the TFPMG-U more attractive in terms of the active mass, cost, efficiency and force density, new configurations of the TFPMG-U are developed, and the generators are designed for 5 MW and 10 MW direct-drive wind turbines.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	X		**R0**	General public			Private web site	X
S1	Reviewed	X		**R1**	Restricted to project members	X		Public web site	
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	
S3	Draft for commends			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

The objectives of this report are:
- assessment of different topologies of permanent magnet (PM) generators for large direct-drive wind turbines
- development of new configurations of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance.

For the assessment, a comparative design of different PM generators for 5 MW and 10 MW direct-drive wind turbines is represented in chapter 2, using the analytical models developed in a previous report, D 1B2.b.4.
For the development, new transverse flux permanent magnet (TFPM) generator with multiple-modules of rotor and stator is proposed in chapter 3.

2. Comparative design of PM generators for large direct-drive wind turbines

The objective of this chapter is to assess different topologies of permanent magnet (PM) generators for large direct-drive wind turbines. For the assessment, a comparative design of different PM generators for 5 MW and 10 MW direct-drive wind turbines is represented using the analysis models derived in a previous report, D 1B2.b.4.
This chapter consists of the following outline. First, a selection of types of PM generators for large direct-drive wind turbines is discussed. A surface-mounted radial flux permanent magnet (RFPM) machine and four different flux-concentrating transverse flux permanent magnet (TFPM) machines are chosen for a comparative design. Next, the electromagnetic aspects of the chosen PM generators are designed, taking into consideration of the parameters of 5 MW and 10 MW direct-drive wind turbines. These generators are assessed based on the criteria of mass, loss, cost, efficiency and force density.

2.1 Selection of generator types for large direct-drive wind turbines

Different topologies of permanent magnet (PM) machines have been discussed in a number of references as discussed in a previous report (Deliverable No.: D 1B2.b.1). Out of these different PM machines, surface-mounted radial flux permanent magnet (RFPM) machines have been discussed as a better choice for large direct-drive wind turbines in references. Considering the force density of electric machines, flux-concentrating TFPM machines have been discussed as potentially having higher force density than surface-mounted TFPM machine topologies. Single winding topologies of TFPM machines have been discussed as a suitable type for simpler construction and lower copper losses. Therefore, the following five different types of PM generators have been selected for the comparative design in this chapter.
1) ***RFPMG****:* a slotted surface-mounted RFPM generator with full pitch windings and inner rotor
2) ***TFPMG-U****:* a single-sided, single winding flux-concentrating TFPM generator with U-core
3) ***TFPMG-C****:* a double-sided, single winding flux-concentrating TFPM generator with C-core
4) ***TFPMG-U/PR****:* a single-sided, single winding flux-concentrating TFPM generator with U-core and passive rotor
5) ***TFPMG-C/PR****:* a double-sided, single winding flux-concentrating TFPM generator with C-core and passive rotor

Linearized structures of the selected five different PM generators are illustrated in Figures 2-1 to 2-5. Figure 2-1 depicts a surface-mounted RFPM generator with PMs and a back yoke in the rotor, and windings, slots and a back yoke in the stator (***RFPMG***). Figure 2-2 depicts the single-sided air gap TFPM generator which consists of flux-concentrating cores with PMs in the rotor, and U-cores with single winding in the stator (***TFPMG-U***). The double-sided air gap TFPM generator with flux-concentrating cores and PMs in the rotor, and with C-cores and single windings in the stator (***TFPMG-C***) is depicted in Figure 2-3. Figure 2-4 depicts the single-sided air gap TFPM generator which consists of flux-concentrating U-cores, PMs and single windings in the stator with a passive rotor (***TFPMG-U/PR***). The double-sided air gap TFPM generator with flux-concentrating C-cores, PMs and single windings in the stator with a passive rotor (***TFPMG-C/PR***) is depicted in Figure 2-5.

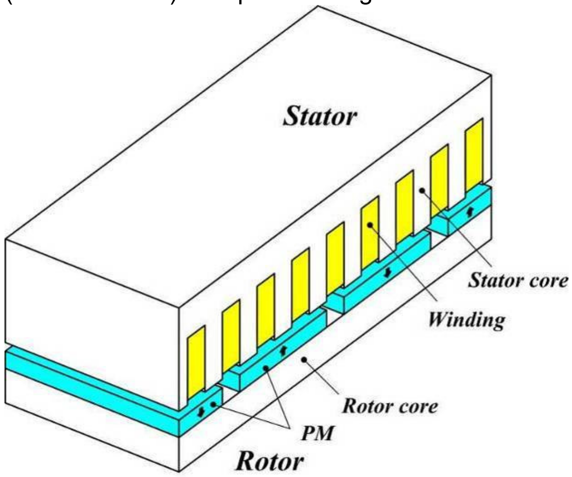


Figure 2-1: *Surface-mounted RFPM generator (RFPMG)*

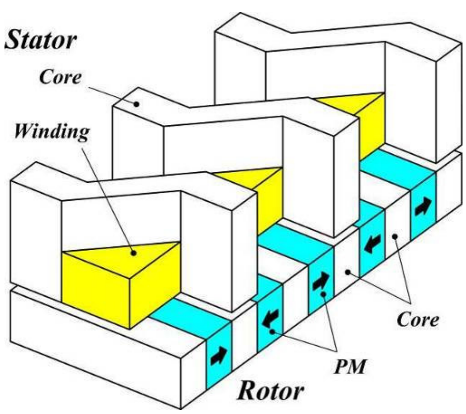


Figure 2-2: *Single-sided single winding flux-concentrating TFPM generator with a U-core (TFPMG-U)*

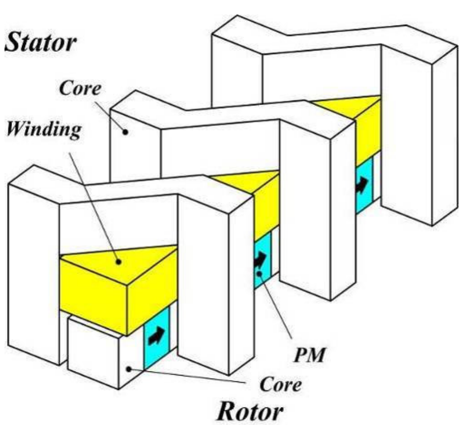


Figure 2-3: *Double-sided single winding flux-concentrating TFPM generator with a C-core (TFPMG-C)*

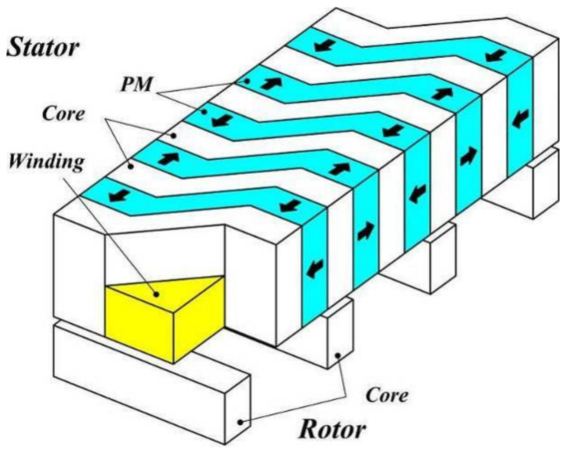


Figure 2-4: *Single-sided single winding flux-concentrating TFPM generator with a U-core (TFPMG-U/PR)*

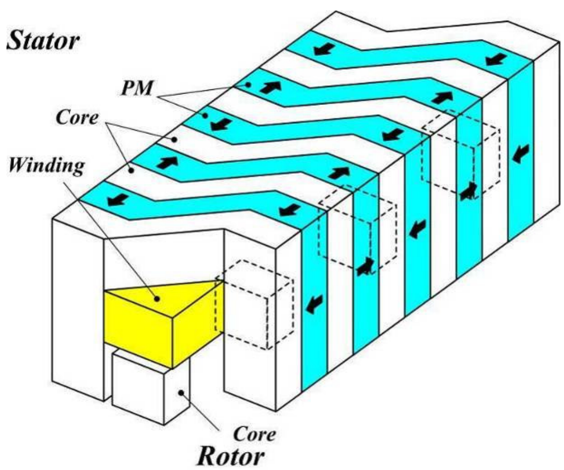


Figure 2-5: *Double-sided single winding flux-concentrating TFPM generator with a C-core (TFPMG-C/PR)*

2.2 Comparative design of PM generators for direct-drive wind turbines

Using the formulations and analytical models of PM machines discussed in the report, D 1B2.b.4, a surface-mounted RFPM generator (***RFPMG***) and four different TFPM generators (***TFPMG-U***, ***TFPMG-C***, ***TFPMG-U/PR*** and ***TFPMG-C/PR***) selected in the last section are designed for 5 MW and 10 MW direct-drive wind turbines in this section. TABLE 2-1 gives the parameters of the wind turbines and the requirements for the generators.
Cost models and material characteristics [1] of the generators are given in TABLE 2-2 and TABLE 2-3, respectively.

TABLE 2-1
WIND TURBINE PARAMETERS AND GENERATOR REQUIREMENTS

Wind turbine parameters		
Rated grid power, P	5 [MW]	10 [MW]
Rotor blades diameter, D_r	126 [m]	178 [m]
Rotor blades tip speed, v_{tip}	80 [m/s]	80 [m/s]
Rated rotor speed, N	12.1 [rpm]	8.6 [rpm]
Generator requirements		
Nominal power, P_{gennom}	5.56 [MW]	11.12 [MW]
Nominal torque, T_{gennom}	4.38 [MNm]	12.38 [MNm]

TABLE 2-2
GENERATOR COST MODELS

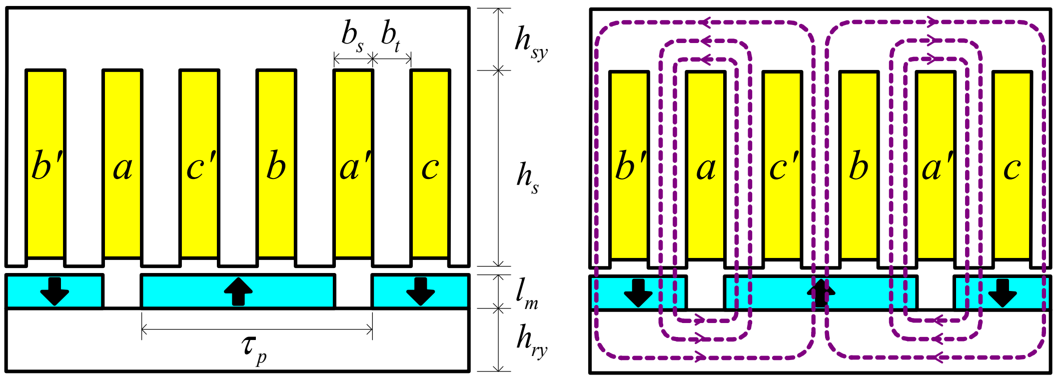
Cost models	
Iron core cost, k_{Fe}	3 [€/kg]
Copper cost, k_{Cus}	15 [€/kg]
Permanent magnet cost, k_{pm}	25 [€/kg]

TABLE 2-3
GENERATOR MATERIAL CHARACTERISTICS

Material characteristics		
Specific hysteresis losses of iron cores	Laminated electrical steel core	4 [W/kg] at 1.5 [T] and 50 [Hz]
	SMC core (Somaloy 700)	7.93 [W/kg] at 1.3 [T] and 50 [Hz] in [2] - Sample core size: D_o: 57.2 [mm], D_i: 26.4 [mm], H: 5.6 [mm]
Specific eddy current losses of iron cores,	Laminated electrical steel core	1 [W/kg] at 1.5 [T] and 50 [Hz]
	SMC core (Somaloy 700)	0.17 [W/kg] at 1.3 [T] and 50 [Hz] in [2] - Sample core size: D_o: 57.2 [mm], D_i: 26.4 [mm], H: 5.6 [mm]
Resistivity of copper, ρ_{Cu}		0.025 [μΩm]
Remanent flux density of permanent magnets, B_{rm}		1.2 [T]
Relative recoil permeability of permanent magnets, μ_{rm}		1.05 [-]
Permeability of free space, μ_0		$4\pi\times10^{-7}$ [H/m]
Density	Iron core, ρ_{Fe}	Lamination steel: 7700 [kg/m^3] SMC core: 7440 [kg/m^3]
	Permanent magnet, ρ_{pm}	7600 [kg/m^3]
	Copper, ρ_{Cumass}	8900 [kg/m^3]

2.2.1 RFPM generator

Figure 2-6 depicts the external shape, the dimensional parameters and the flux paths of the surface-mounted RFPM generator with full pitch windings (***RFPMG***). In the figure, dotted lines with arrows represent the flux paths.



(a) (b)

Figure 2-6: *Dimensional parameters and flux paths of RFPMG*

TABLE 2-4 gives the design results with dimensions, flux density, current and no-load voltage of ***RFPMG*** for 5 MW and 10 MW direct-drive wind turbines. The parameters and dimensions of the ***RFPMG*** in TABLE 2-4 were determined by the dimensions and parameters discussed in TABLE 1 in the report, D 1B2.b.4. TABLE 2-5 gives the design results with mass, cost and losses of ***RFPMG*** for 5 MW and 10 MW direct-drive wind turbines.

TABLE 2-4
DIMENSIONS, CURRENT, AIR-GAP FLUX DENSITY AND NO-LOAD VOLTAGE OF RFPMG FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

	5 [MW]	10 [MW]
Aspect ratio of generator, $K_{rad} = \frac{l_s}{D_g}$ [-]	0.27	0.3
Air gap diameter (Generator rotor diameter), D_g [m]	6.36	8.68
Axial length of generator, l_s [m]	1.72	2.61
Air gap length, l_g [mm]	6.36	8.68
Magnet height, l_m [mm]	15.9	21.7
Stator diameter, D_s [m]	6.37	8.699
Number of phases, m [-]	3	3
Stator slot pitch, τ_s [mm]	33	33
Number of slots per pole per phase, q [-]	1	1
Pole pitch, τ_p [mm]	100	99.7
Number of pole pairs, p [-]	100	137
Rotor pole width, b_p [mm]	80	80
Stator slot width, b_s [mm]	15	14.96
Stator tooth width, b_t [mm]	18	18
Stator slot height, h_s [mm]	80	80
Stator yoke height, h_{sy} [mm]	40	40
Rotor yoke height, h_{ry} [mm]	40	40
Air gap area, $A_g \left(= \pi D_g l_s\right)$ [m^2]	34.29	71.04
Nominal current, I_{snom} [A]	606.2	551.9
Number of conductors per slot, N_{cslot} [turns]	3.35	3.35
Peak flux density in the air-gap, $\hat{B}_g$ (= $\hat{B}_{pm}$) [T]	0.97	1.07
RMS value of no-load voltage, E [V]	3057.3	6716.1
Force density, F_d [kN/m^2]	40.16	40.16

TABLE 2-5
ACTIVE MASS, COST AND LOSS OF THE SURFACE-MOUNTED RFPM GENERATOR FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

Mass of active material		5 [MW]	10 [MW]
Mass of active material [kg]	Copper mass, M_{Cus}	7,491	14,961
	Stator core mass, M_{Fes}	22,530	46,542
	Permanent magnets mass, M_{pm}	3,314	9,374
	Rotor core mass, M_{Fer}	10,443	21,669
	Generator mass, M_{gen}	43,805	92,546
Cost of active material [€]	Copper cost, K_{Cus}	112,365	224,421
	Stator core cost, K_{Fes}	67,671	139,625
	Permanent magnets cost, K_{pm}	82,857	234,350
	Rotor core cost, K_{Fer}	31,329	65,006
	Generator cost, K_{gen}	294,222	663,403
Loss [kW]	Copper loss, P_{Cus}	162	270.1
	Stator core loss, P_{Fes}	25.3	60.3
	Generator loss, P_{gen}	187.3	330.4
Efficiency, η_{nom} [%]		96.6	97

2.2.2 TFPM generator

Figure 2-7, Figure 2-8, Figure 2-9 and Figure 2-10 depict the external shapes, the dimensional parameters and the flux paths of the four different flux-concentrating TFPM generators (***TFPMG-U***, ***TFPMG-C***, ***TFPMG-U/PR*** and ***TFPMG-C/PR***). In the figures, dotted lines with arrows represent the flux paths simplified.

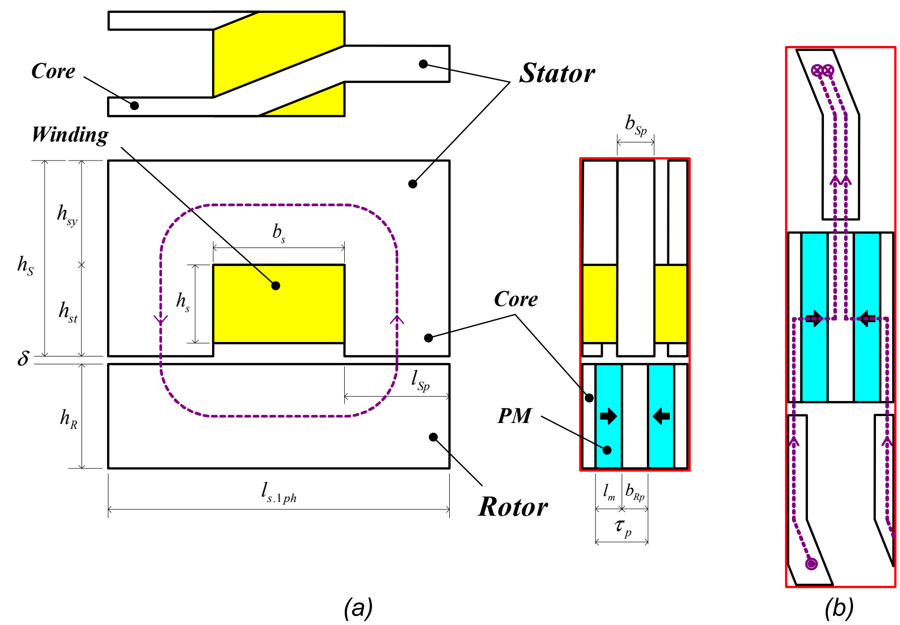


Figure 2-7: *Dimensional parameters and flux paths of TFPMG-U*

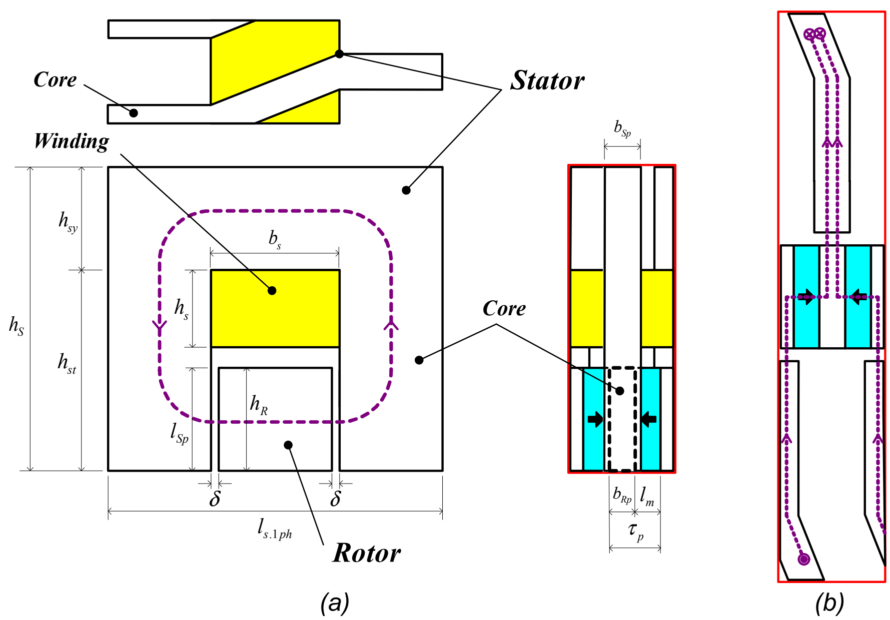
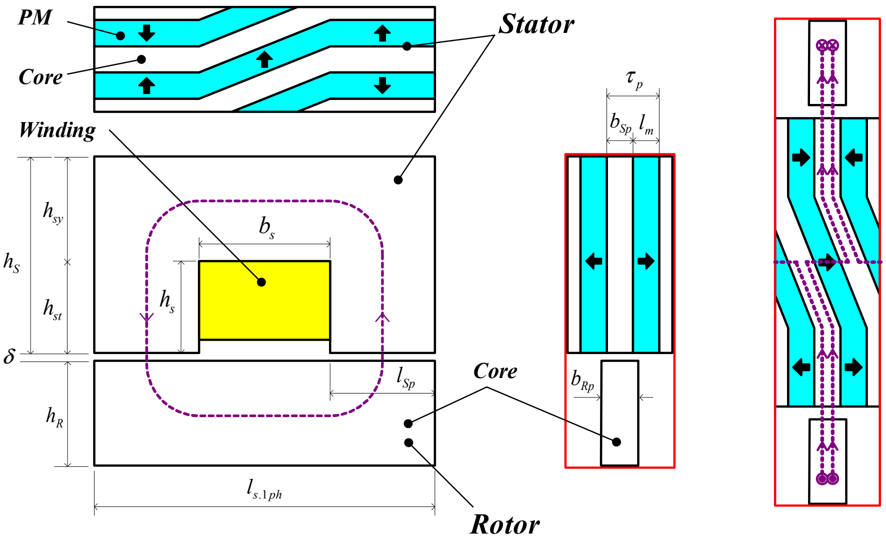
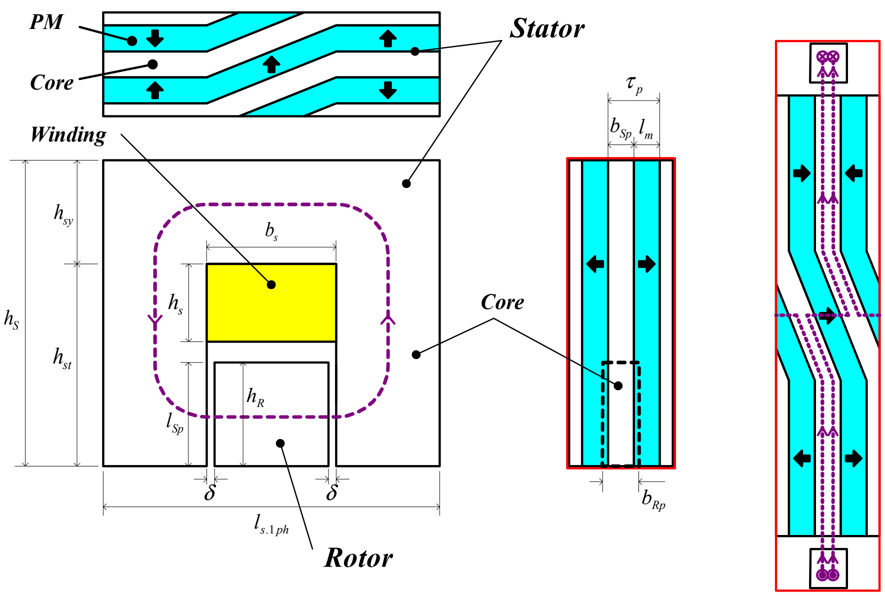


Figure 2-8: *Dimensional parameters and flux paths of TFPMG-C*



(a) (b)

Figure 2-9: *Dimensional parameter and flux paths of TFPMG-U/PR*



(a) (b)

Figure 2-10: *Dimensional parameters and flux paths of TFPMG-C/PR*

As discussed in the report, D 1B2.b.4, the leakage fluxes of TFPM machines are much larger than the leakage fluxes of RFPM machines with full pitch windings. Therefore, the leakage fluxes are included in the equivalent circuits of magnetic reluctances of TFPM generators as illustrated in Figure 2-11 and Figure 2-12. Figure 2-11 depicts the equivalent circuits of the magnetic reluctances of ***TFPMG-U*** and ***TFPMG-C***. Figure 2-12 depicts the equivalent circuits of the magnetic reluctances of ***TFPMG-U/PR*** and ***TFPMG-C/PR***.

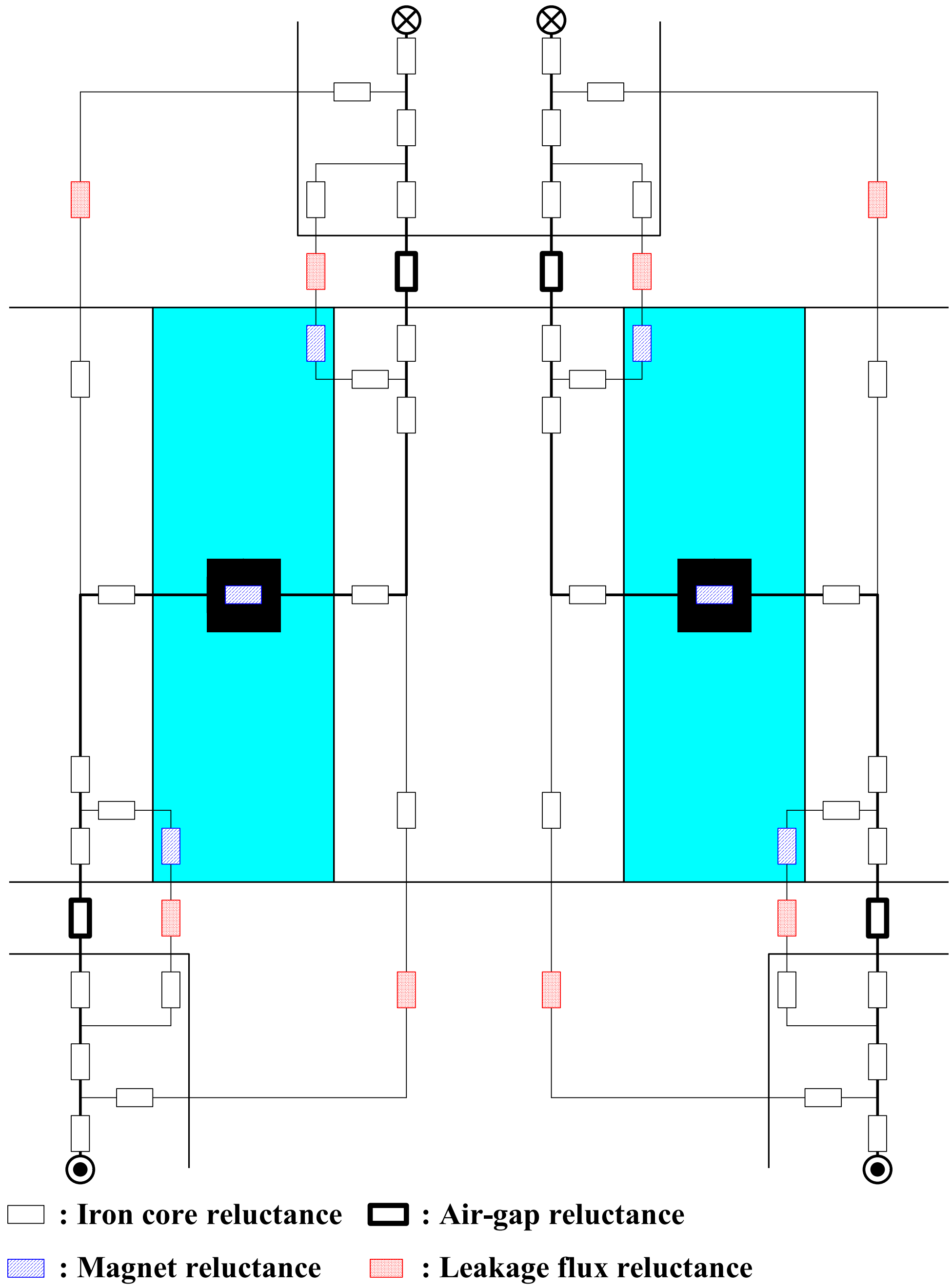


Figure 2-11: *Equivalent circuits of magnetic reluctances of TFPMG-U and TFPMG-C*

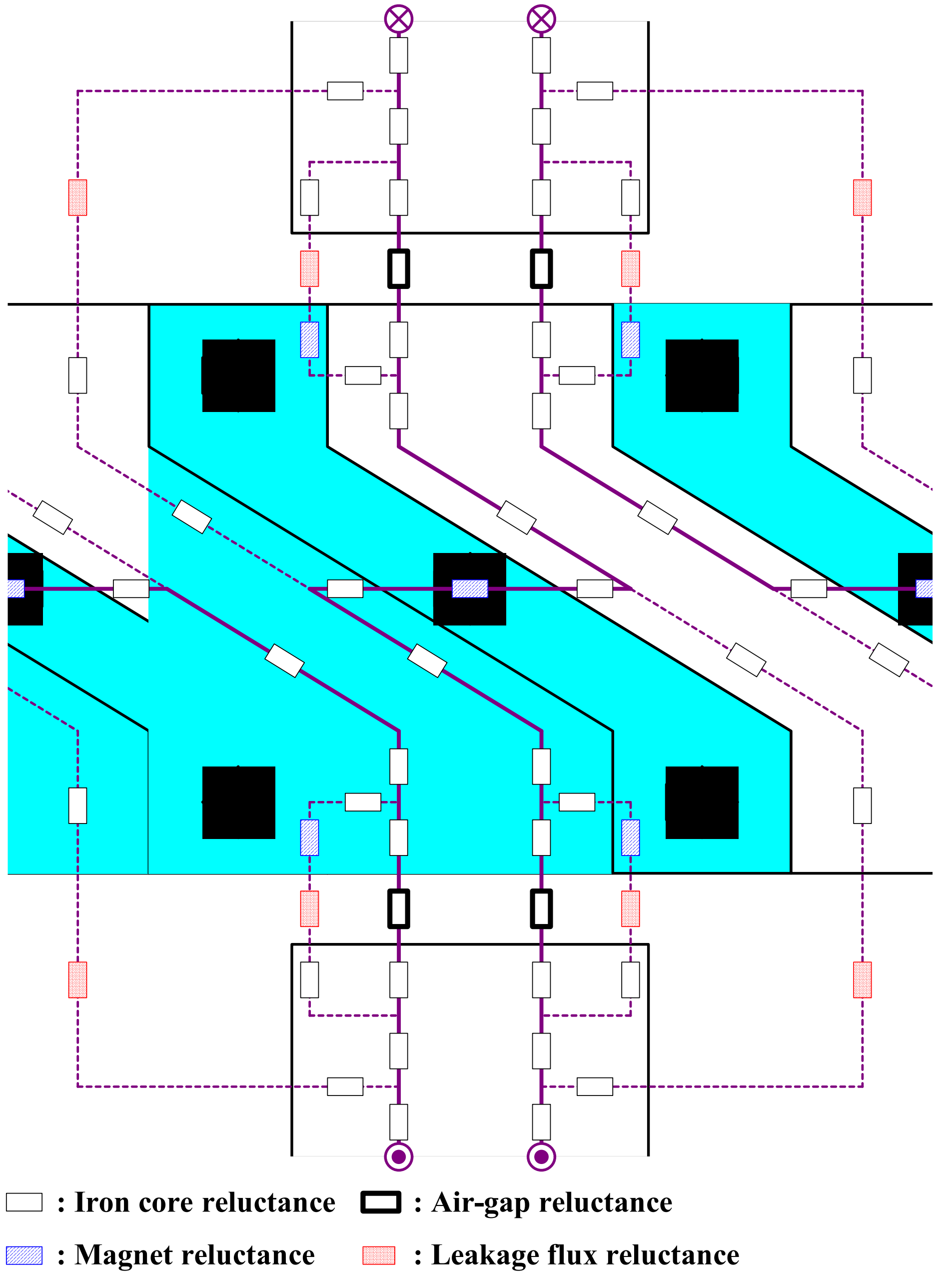


Figure 2-12: *Equivalent circuits of magnetic reluctances of TFPMG-U/PR and TFPMG-C/PR*

TABLE 2-6 gives the design results with dimensions, flux density, current and no-load voltage of the four different TFPM generators for 5 MW and 10 MW direct-drive wind turbines. In the design, the dimensions and parameters of the TFPM generators were determined by the dimensional parameters discussed in the report, D 1B2.b.4. TABLE 2-7 gives the design results with mass, cost and losses of the four different TFPM generators for 5 MW and 10 MW direct-drive wind turbines.

TABLE 2-6
DIMENSIONS, CURRENT, AIR-GAP FLUX DENSITY AND NO-LOAD VOLTAGE OF TFPMG-U, TFPMG-C, TFPMG-U/PR AND TFPMG-C/PR FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

	TFPMG-U		TFPMG-C		TFPMG-U/PR		TFPMG-C/PR	
	5 MW	10 MW	5 MW	10 MW	5 MW	10 MW	5 MW	10 MW
Air gap diameter, D_g [m]	6.36	8.68	6.36	8.68	6.36	8.68	6.36	8.68
Axial length of generator, l_s [m]	1.03	1.464	1.03	1.464	1.02	1.468	1.06	1.515
Air gap length, l_g [mm]	6.36	8.68	6.36	8.68	6.36	8.68	6.36	8.68
Magnet height, l_m [mm]	25.4	34.7	25.4	34.7	25.4	34.7	25.4	34.7
Stator diameter, D_s [m]	6.37	8.699	6.37	8.699	6.37	8.699	6.37	8.699
Number of phase, m [-]	3	3	3	3	3	3	3	3
Pole pitch, τ_p [mm]	63.6	86.9	63.6	86.9	63.6	86.9	63.6	86.9
Number of pole pairs, p [-]	157	157	157	157	157	157	157	157
Pole width, b_{sp} [mm]	50.9	69.5	50.9	69.5	50.9	69.5	50.9	69.5
Stator slot width, b_s [mm]	80.8	94.4	80.8	94.4	80.8	94.4	80.8	94.4
Stator pole length, l_{sp} [mm] (=Stator tooth width, b_{st})	130.4	196.8	130.4	196.8	130.1	197.4	135.9	205.3
Stator slot height, h_s [mm]	80.8	94.4	80.8	94.4	80.8	94.4	80.8	94.4
Stator yoke height, h_{sy} [mm]	130.4	196.8	130.4	196.8	130.1	197.4	135.9	205.3
Rotor height, h_R [mm]	130.4	196.8	291.6	528.1	130.1	197.4	135.9	205.3
Air gap area, $A_g \left(= \pi D_g l_s\right)$ [m^2]	20.47	39.93	20.47	39.93	20.43	40.03	21.12	41.31
Nominal current, I_{snom} [A]	606.2	551.9	606.2	551.9	606.2	551.9	606.2	551.9
Number of conductors per slot, N_{cslot} [turn] (= Number of conductors per phase)	20.98	31.46	20.98	31.46	20.98	31.46	20.98	31.46
Peak flux density in air-gap, $\hat{B}_g$ [T]	1.59	1.6	0.76	0.65	1.66	1.65	1.53	1.54
RMS value of no-load voltage, E [V]	3057	6,716	3058	6,716	3059	6,716	3057	6,716
Force density, F_d [kN/m^2]	67.3	71.5	67.3	71.5	67.4	71.3	65.2	69.1

TABLE 2-7
ACTIVE MASS, COST AND LOSS OF TFPMG-U, TFPMG-C, TFPMG-U/PR AND TFPMG-C/PR FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

	TFPMG-U		TFPMG-C		TFPMG-U/PR		TFPMG-C/PR	
	5 MW	10 MW	5 MW	10 MW	5 MW	10 MW	5 MW	10 MW
Mass of active material [kg]								
Copper, M_{Cus}	2,294	4,269	2,294	4,269	2,294	4,269	2,294	4,269
Stator core, M_{Fes}	11,699	32,429	25,263	83,044	17,487	48,888	28,552	82,778
Permanent magnets, M_{pm}	8,114	23,888	3,615	10,114	11,909	33,293	19,444	56,372
Rotor core, M_{Fer}	11,915	35,077	5,308	14,852	7,910	23,519	1,648	3,849
Generator, M_{gen}	34,021	95,662	36,480	112,281	39,601	109,969	51,938	147,268
Cost of active material [€]								
Copper, K_{Cus}	34,410	64,035	34,410	64,035	34,410	64,035	34,410	64,035
Stator core, K_{Fes}	35,097	97,286	75,790	249,133	52,462	146,664	85,656	248,334
Permanent magnets, K_{pm}	202,846	597,188	90,371	252,872	297,722	832,320	486,099	1,409,302
Rotor core, K_{Fer}	35,744	105,230	15,924	44,558	23,732	70,557	4,945	11,546
Generator, K_{gen}	308,097	863,741	216,495	610,599	408,326	1,113,576	611,100	1,733,217
Loss [kW]								
Copper, P_{Cus}	58.5	108.8	58.5	108.8	58.5	108.8	58.5	108.8
Stator core, P_{Fes}	34.8	68.6	75.1	175.6	92.9	182.7	138.9	286.1
Rotor core, P_{Fer}	60.4	126.4	11.2	18.4	24.5	51.2	4.8	7.9
Generator, P_{gen}	153.6	303.8	144.8	302.9	175.9	342.7	202.2	402.9
Efficiency, η_{nom} [%]								
	97.2	97.3	97.4	97.3	96.8	96.9	96.4	96.4

2.3 Comparison of PM generators

Figure 2-13 depicts the active mass of five different PM generators which are ***RFPMG***, ***TFPMG-U***, ***TFPMG-C***, ***TFPMG-U/PR*** and ***TFPMG-C/PR*** for 5 MW direct-drive wind turbines. Among these five generators, ***TFPMG-U*** seems the lightest generator and ***TFPMG-C/PR*** seems the heaviest generator. The copper mass of ***RFPMG*** is larger than TFPM generators. Figure 2-14 depicts the losses of the five different generators. ***TFPMG-C/PR*** has the largest loss and ***TFPMG-C*** has the smallest loss among the five different generators. The flux density in the stator cores of ***TFPMG-U/PR*** is higher than the flux density in the stator cores of ***RFPMG***. Therefore, the stator core loss of ***TFPMG-U/PR*** is larger than the stator core loss of ***RFPMG***, even though stator core mass of ***TFPMG-U/PR*** is smaller than the stator core mass of ***RFPMG***. Figure 2-15 depicts the cost of the five different generators. It shows that ***TFPMG-C*** is the cheapest generator, ***RFPMG*** is the 2nd cheapest generator and ***TFPMG-C/PR*** is the most expensive generator.

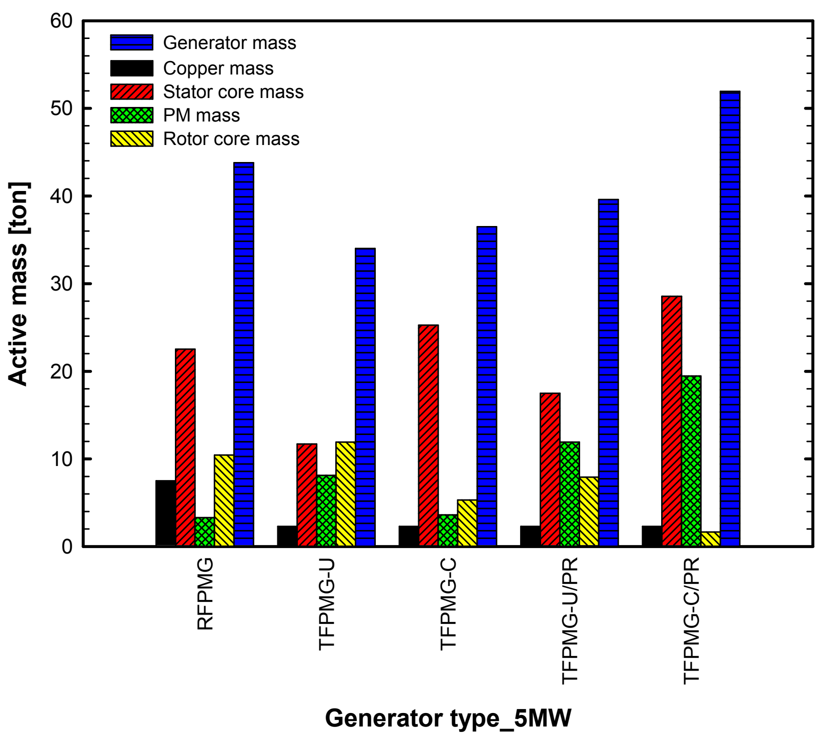


Figure 2-13: *Active mass comparison of different 5 MW PM generators*

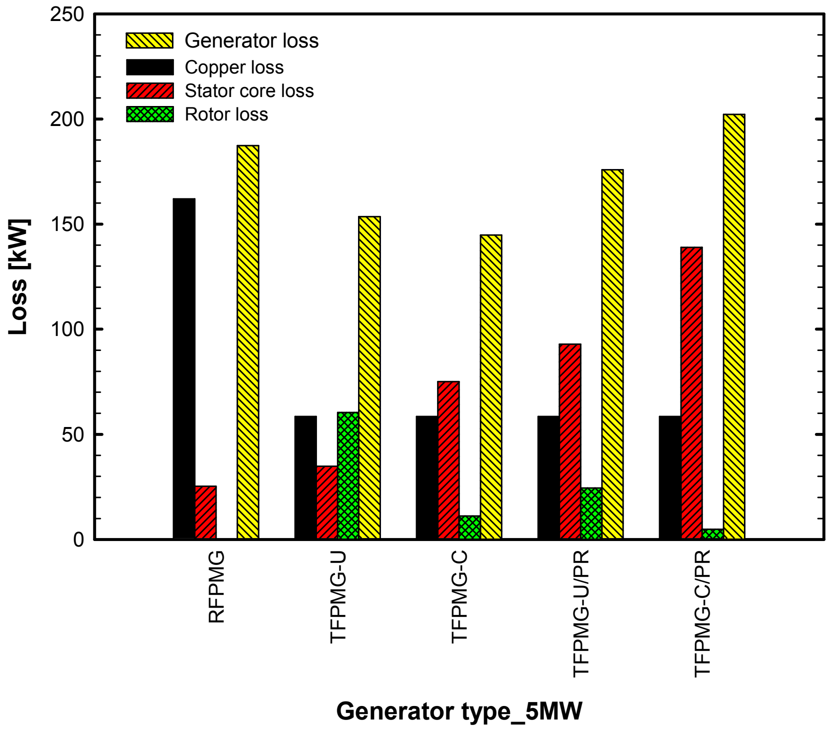


Figure 2-14: *Loss comparison of different 5 MW PM generators*

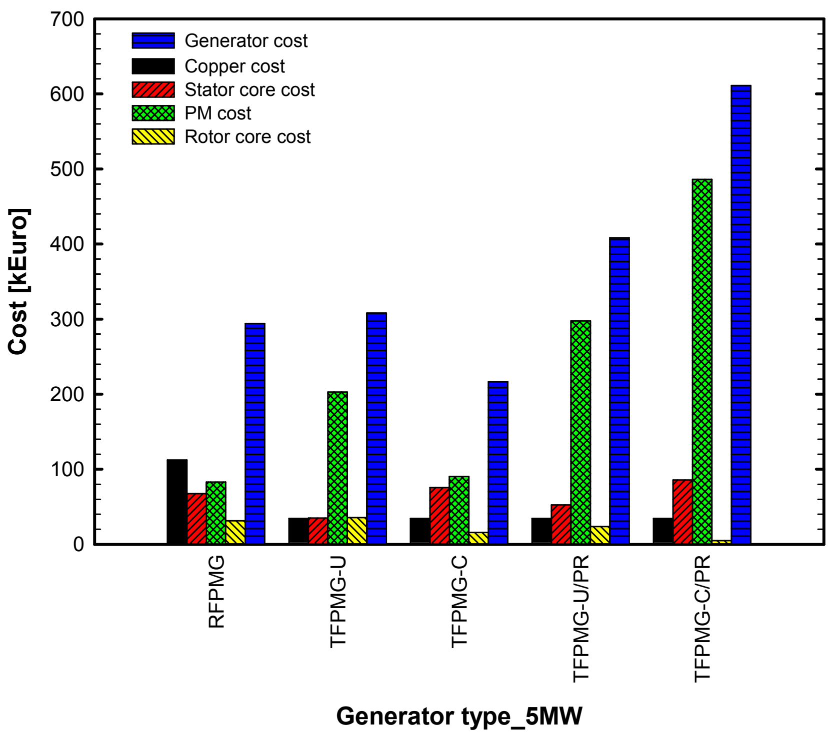


Figure 2-15: *Cost comparison of different 5 MW PM generators*

Figure 2-16 depicts the active mass of the five different PM generators for 10 MW direct-drive wind turbines. Among these five generators, ***RFPMG*** seems the lightest generator, ***TFPMG-U*** seems the 2nd lightest generator and ***TFPMG-C/PR*** seems the heaviest generator. The copper mass of ***RFPMG*** is larger than TFPM generators. Figure 2-17 depicts the losses of the five different generators. ***TFPMG-C/PR*** has the largest loss, and ***TFPMG-U*** and ***TFPMG-C*** has the smallest loss among the five different generators.

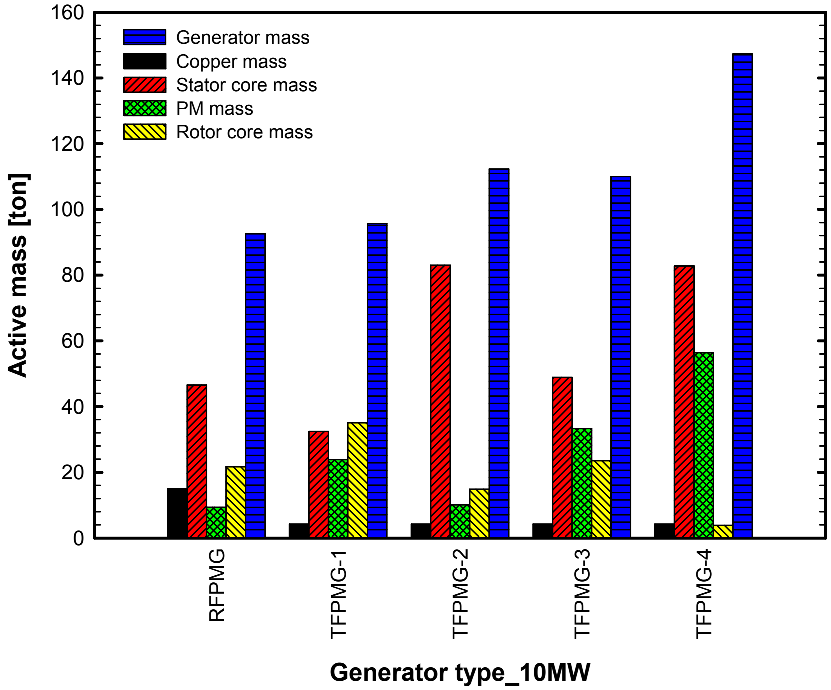


Figure 2-16: *Active mass comparison of different 10 MW PM generators*

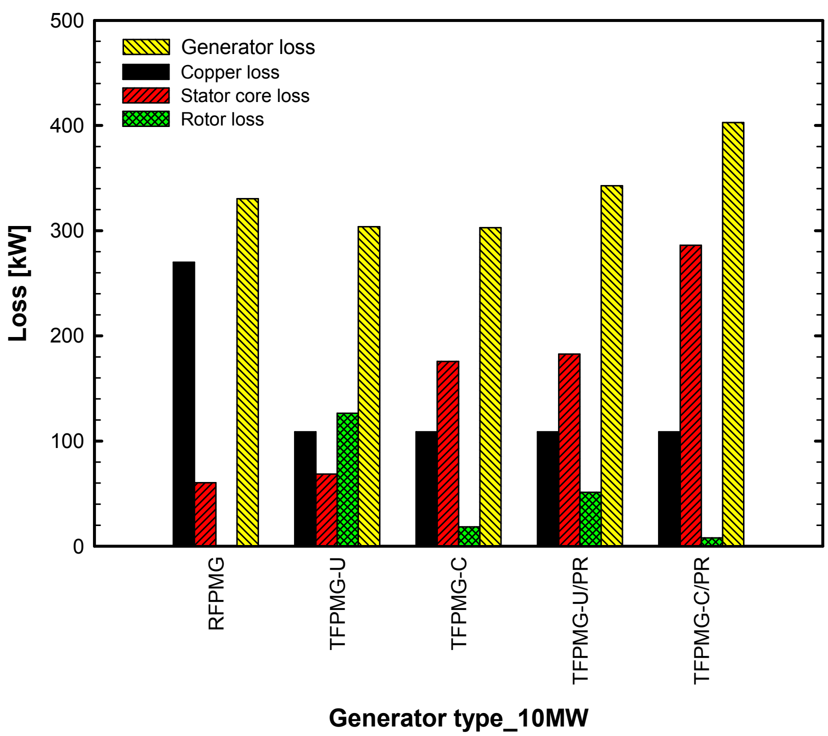


Figure 2-17: *Loss comparison of different 10 MW PM generators*

Figure 2-18 depicts the cost of the five different generators. It shows that ***TFPMG-C*** is the cheapest generator, ***RFPMG*** is the 2nd cheapest generator and ***TFPMG-C/PR*** is the most expensive generator.

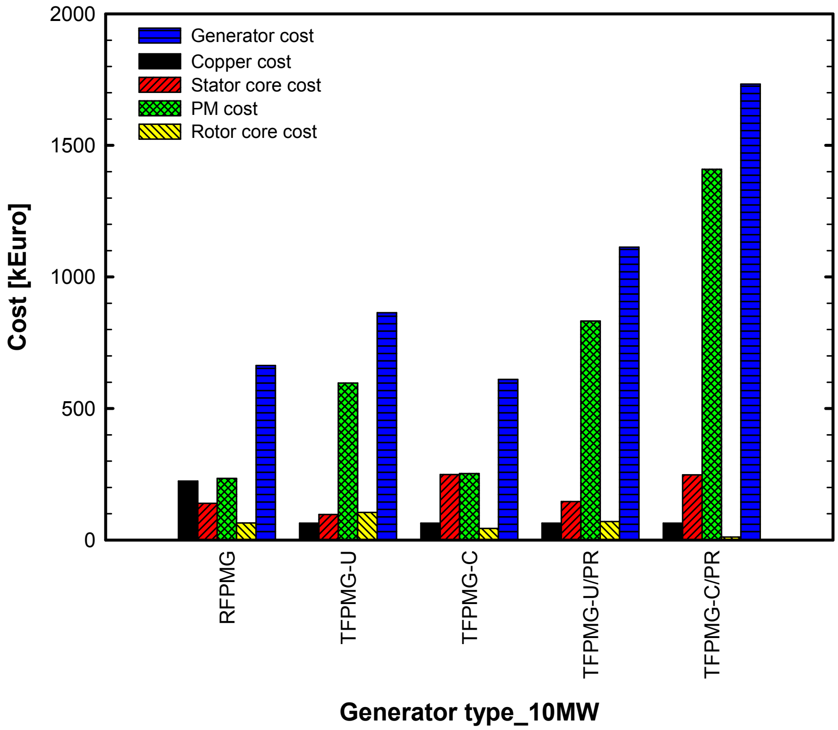


Figure 2-18: *Cost comparison of different 10 MW PM generators*

Figure 2-19 depicts the efficiency and the force density of the five different generators for 5 MW and 10 MW direct-drive wind turbines. The efficiencies of those generators obtained through the analytical design are between 96.4 % and 97.4 %. The differences of efficiency among those generators are not large. Force densities of TFPM generators are between 65.2 and 71.5 [kN/m^2], which are higher than the force density of ***RFPMG***, 40.16 [kN/m^2].

Figure 2-20 depicts the cost/torque ratio and the mass/torque ratio of the five different generators. ***TFPMG-C*** shows the highest cost-competitiveness among different generators for both 5 MW and 10 MW wind turbines.

For 5 MW, the cost/torque ratio of ***TFPMG-C*** is 49.4 [Euro/kNm], the ratio of ***RFPMG*** is 67.2 [Euro/kNm] and the ratio of ***TFPMG-U*** is 70.3 [Euro/kNm]. The active mass/torque ratio of ***TFPMG-U*** that is the lightest generator is 7.77 [kg/kNm], and the ratio of ***RFPMG*** that is the heaviest generator is 10 [kg/kNm].

For 10 MW, the cost/torque ratio of ***TFPMG-C*** is 49.3 [Euro/kNm], the ratio of ***RFPMG*** is 53.6 [Euro/kNm] and the ratio of ***TFPMG-U*** is 69.8 [Euro/kNm]. ***RFPMG*** is also addressed as the 2nd cheapest generator, but the difference between the ratios of ***RFPMG*** and ***TFPMG-U*** is larger than the difference at 5 MW. The active mass/torque ratios of ***RFPMG***, ***TFPMG-U***, ***TFPMG-C***, ***TFPMG-U/PR*** and ***TFPMG-C/PR*** are 7.48, 7.73, 9.07, 8.88 and 11.9 [kg/kNm], respectively.

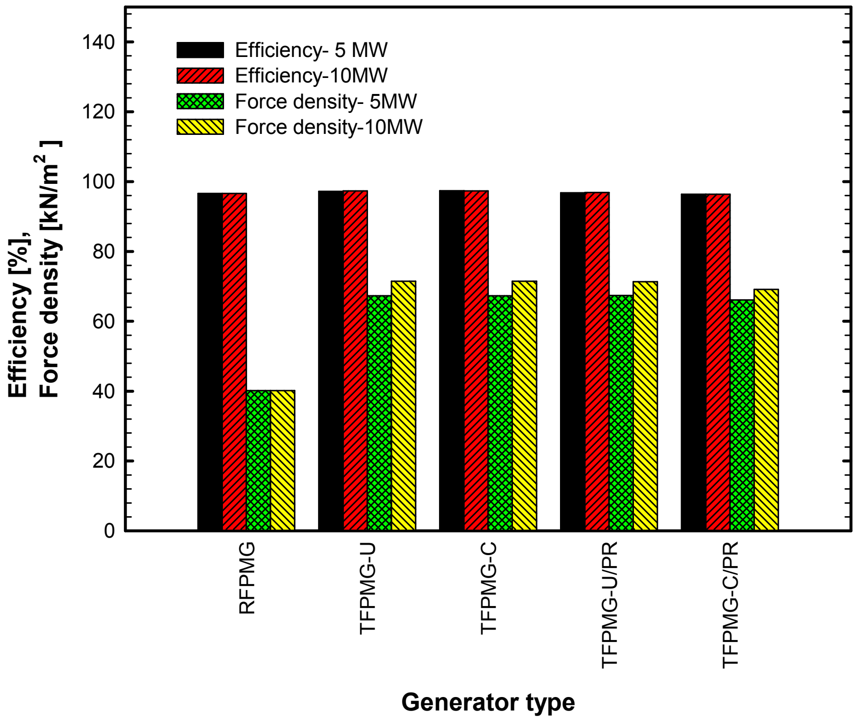


Figure 2-19: *Comparison of efficiency and force density of different 5 MW and 10 MW PM generators*

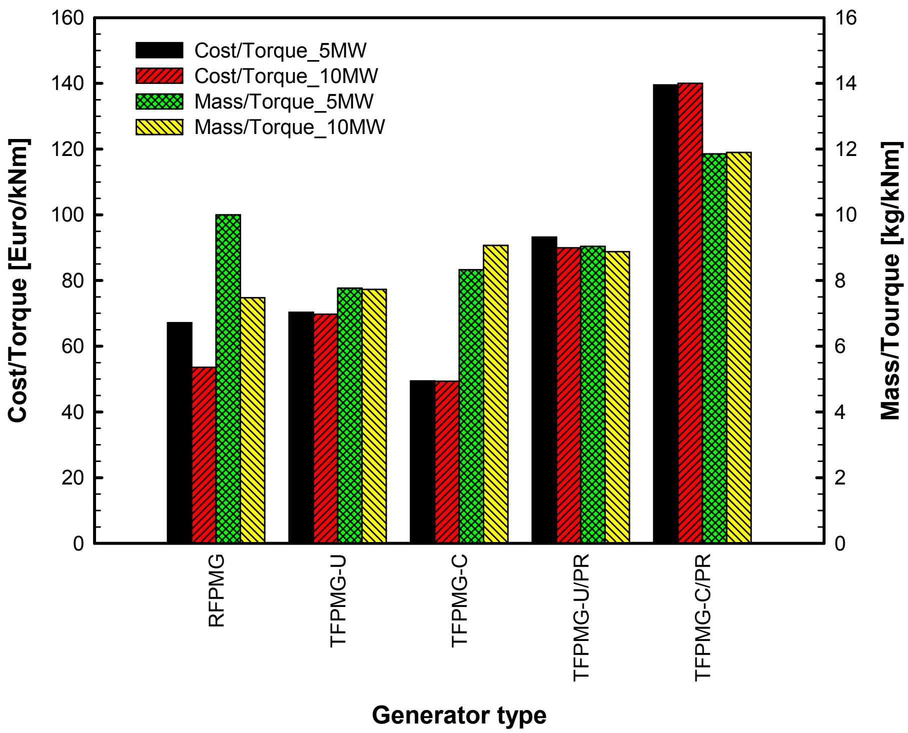


Figure 2-20: *Comparison of cost/torque and mass/torque of different 5 MW and 10 MW PM generators*

TABLE 2-8 gives an overview of comparison results of the five PM generators based on the criteria of active mass, cost, efficiency and force density. In the table, the strengths of the five generators are indicated with following marks.

- ++ : very strong
- + : strong
- Δ : middle
- - : weak
- -- : very weak

TABLE 2-8
COMPARISON OF THE FIVE DIFFERENT PM GENERATORS FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

		RFPMG	***TFPMG-U***	***TFPMG-C***	***TFPMG-U/PR***	***TFPMG-C/PR***
Active mass	5 MW	-	++	+	Δ	--
	10 MW	++	+	-	Δ	--
Cost	5 MW	+	Δ	++	-	--
	10 MW	+	Δ	++	-	--
Efficiency	5 MW	- (96.6%)	+ (97.2%)	++ (97.4%)	Δ (96.8%)	-- (96.4%)
	10 MW	Δ (97%)	++ (97.3%)	++ (97.3%)	- (96.9%)	-- (96.4%)
Force density	5 MW	--	++	++	++	+
	10 MW	--	++	++	+	-

2.4 Conclusions

In order to assess different topologies of permanent magnet (PM) generators for large direct-drive wind turbines, a comparative design of different PM generators for 5 MW and 10 MW direct-drive wind turbines was discussed in this chapter.
From the overview of different PM machines and the identification of the active mass-competitiveness of those machines in a previous report (Deliverable No.: D 1B2.b.1), the following PM generators were selected for the comparative design in this chapter.

- ***RFPMG***: A slotted surface-mounted radial flux permanent magnet generator with full pitch windings, inner rotor and rare earth magnets
- ***TFPMG-U***: A single-sided, single winding flux-concentrating transverse flux permanent magnet generator with U-core
- ***TFPMG-C***: A double-sided, single winding flux-concentrating transverse flux permanent magnet generator with C-core
- ***TFPMG-U/PR***: A single-sided, single winding flux-concentrating transverse flux permanent magnet generator with U-core and passive rotor
- ***TFPMG-C/PR***: A double-sided, single winding flux-concentrating transverse flux permanent magnet generator with C-core and passive rotor

Using the formulations and the analytical models developed in the report, D 1B2.b.4, the selected five PM generators were electromagnetically designed for 5 MW and 10 MW direct-drive wind turbines. In the design, the electromagnetic dimensions and parameters of the generators were determined by the dimensions and parameters discussed in the report, D 1B2.b.4. These five generators were assessed based on the criteria of active mass, loss, cost, efficiency and force density. From the comparative design, the following results were obtained:

- ***TFPMG-U*** was addressed as the lightest generator whose active mass is 78 [%] of the mass of ***RFPMG*** for 5 MW wind turbines.
- In the design of the generators for 10 MW wind turbines, ***RFPMG*** was addressed as the lightest generator. ***TFPMG-U*** was addressed as the second lightest generator whose active mass is 3.3 [%] larger than the mass of ***RFPMG***.
- ***TFPMG-C*** had the smallest loss and the lowest cost compared to the other generators for both 5 MW and 10 MW turbines.
- ***TFPMG-C/PR*** was addressed as the generator with the largest mass, the highest cost and the largest loss among the five different generators for both 5 MW and 10 MW turbines.
- ***TFPMG-U/PR*** and ***TFPMG-C/PR*** were more expensive than the other generators, since both generators need large mass of permanent magnets which are the most expensive active material.
- ***TFPMG-C*** and ***TFPMG-C/PR*** were more complicated than the others to construct because these two generators have double-sided air gaps.
- Therefore, ***TFPMG-U*** is selected as a suitable generator for large direct-drive wind turbines. In the next chapter, a new configuration of ***TFPMG-U*** with multiple-modules will be discussed for large direct-drive wind turbines.
- In [3] it was concluded that the TFPM machine with toothed rotor was a valuable option in terms of the active mass and cost, if the air gap length can be kept below 1.5 mm. However, the design results in this chapter indicated that the conclusion in [3] is not valid for all configurations of flux-concentrating TFPM machines.

3. TFPM generator with multiple-modules for large direct-drive wind turbines

The objective of this chapter is to develop new configurations of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance.
In the last chapter, five different permanent magnet generators for 5 MW and 10 MW direct-drive wind turbines were designed electromagnetically and compared based on active mass, loss, cost, efficiency and force density. Among the five different generators, the flux-concentrating transverse flux permanent magnet generator with single-sided, single winding and U-core configuration (***TFPMG-U***) was addressed as the lightest generator for 5 MW. The surface-mounted PM generator with full pitch windings (***RFPMG***) was address as the lightest generator for 10 MW. The flux-concentrating TFPM generator with double-sided, single winding and C-core configuration (***TFPMG-C***) had the smallest loss and the lowest cost of active material compared to other generators. However, the ***TFPMG-C*** was more complicated than the others to construct because this generator has double-sided air gaps. This constructive difficulties result in the increase of manufacturing cost. Therefore, the ***TFPMG-U*** is selected as a suitable generator for large direct-drive wind turbines, and the ***RFPMG*** is considered as a reference generator in the design. To make the ***TFPMG-U*** more competitive in terms of the active mass, cost, efficiency and force density, new configurations of the ***TFPMG-U*** are developed, and the generators are designed for 5 MW and 10 MW direct-drive wind turbines in this chapter.
This chapter begins with a description of the new configuration of ***TFPMG-U*** for large direct-drive wind turbines. The proposed TFPM generator consists of multiple-modules of rotor and stator. Secondly, an analytical design model of the proposed TFPM generator is developed, and the model is verified by the experiments of a downscaled TFPM generator. Next, the proposed TFPM generator is designed for 5 MW and 10 MW direct-drive wind turbines. In the design, the number of slots per phase is taken as a variable. The proposed TFPM generators with various numbers of slots are assessed based on active mass, cost, loss, efficiency and force density. The designed generators are also compared with the ***RFPMG*** and the ***TFPMG-U*** discussed in the last chapter.

3.1 TFPM machine with modular structure

Various configurations of transverse flux permanent magnet (TFPM) machines have been proposed and discussed in a number of references. TFPM machines with flux-concentrating configurations have higher force density which results in volume reduction and consequently mass reduction. Thus, the TFPM machine with flux-concentrating configuration is considered for large direct-drive wind generators. This section starts with a description that lists unsuitable configurations of flux-concentrating TFPM machines for large direct-drive wind turbines. Next, suitable configurations of flux-concentrating TFPM machines for large direct-drive wind turbines are listed. Furthermore, a new configuration of a flux-concentrating TFPM machine with multiple-modules is proposed for large direct-drive wind turbines.

Conventional flux-concentrating TFPM machines have the following disadvantages:

- TFPM machines with double-sided air gaps and double windings are complicated to construct.
- Considering the winding structure of TF machines, mostly ring-shaped windings have been used because they lead to lower copper losses and simpler construction. However, the ring-shaped windings with a large diameter are difficult to manufacture and repair.
- When enlarging PM machines, the electromagnetic dimensions of the machines are increased together with an increase in magnet size. Large size of magnets thus makes manufacture more difficult and increases the cost of the machines.

- In order to fix the magnets on the iron cores in the conventional configuration, bonding is widely used. However, when bonding magnets to affix iron cores, the magnets can detach as shown in Figure 3-1(a). In order to avoid the detachment of the magnets, mechanical stacking with bolting discussed in [4] can be an alternative method of affixing the magnets. However, this mechanical stacking and bolting method seems unsuitable for a rotational machine because it is difficult to limit mechanical tolerance accumulated in tangential stacking.
- To increase the volume of magnets with maintaining the length of pole pitch, the height of magnets is increased together with the increase of the height of iron cores in a conventional flux-concentrating TFPM machine configuration as shown in Figure 3-1(b). The increase in magnet volume results in an increase in the volume of iron cores, and consequently the mass and cost of the cores are also increased.
- TF machines have three-dimensional flux paths, thus their construction and manufacture are more complicated than that of longitudinal flux (LF) machines. Due to these disadvantages of TF machines, it would be difficult to achieve their mass production and cost-competitiveness compared to LF machines.

Unsuitable configurations of flux-concentrating TFPM machines for large direct-drive wind turbines described above are summarized as follows:

- double-sided air gap
- double windings
- ring-shaped windings with a large diameter
- large size of iron cores and magnets
- using the bonding method to affix magnets
- assembling magnets and rotor cores in tangential stacking
- difficulties in mass production

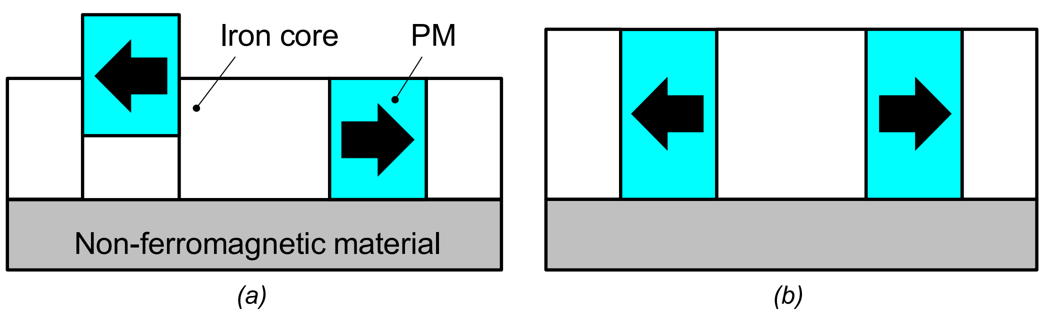


Figure 3-1: *Conventional PMs and iron cores configuration of the flux-concentrating TFPM machine*

In order to overcome the disadvantages of the flux-concentrating TFPM machines with unsuitable configurations described above, the following configurations of the machines are proposed as suitable configurations for large direct-drive wind turbines:

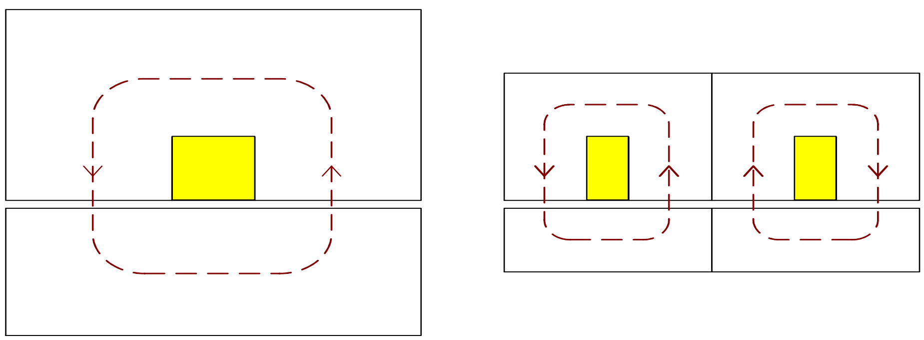
- flux-concentrating TFPM machine with single-sided and single winding configuration
- a multiple-module configuration of TFPM machine with multiple-slots per phase to reduce the active material by shortening flux paths instead of one-module configuration [5]: Electric machines with shorter flux paths enable to reduce the active material, since shorter flux paths result in material reduction by decreasing slot pitch and slot height as illustrated in Figure 3-2.
- racetrack-shaped windings instead of ring-shaped windings: A poly phase transverse flux motor with racetrack-shaped windings was also proposed in [Gla 2002]. However, the end-winding length of the motor is longer than the winding length in the slot, thus its end-winding loss is large. Therefore, a racetrack-shaped winding with short end-winding length is needed for large direct-drive TFPM machines.

- a claw pole configuration of a TFPM machine with an increased iron core area [Ban 2008a][Dub 2004] to produce higher induced voltage, which results in higher force density and lower mass/torque ratio as discussed in a previous report (Deliverable No.: D 1B2.b.1). A generator with an increased iron core area is suitable for increasing the no-load voltage because the voltage is proportional to the iron core area as given in (1).

$$e_p = N_{cslot} B_{core} A_{core} 2\pi f \qquad (1)$$

where e_p is the no-load voltage, N_{cslot} is the number of conductors per slot, B_{core} is the flux density in iron cores, A_{core} is the area of iron cores to link the flux, and f is the frequency.

- a configuration with segmented iron cores and segmented magnets in order to facilitate manufacture for large direct-drive generators
- modular structures of the rotor and stator in order to facilitate manufacturing and maintenance



(a) (b)

Figure 3-2: *Configurations with one slot and two slots per a phase*

Figure 3-3 depicts a sketch of the proposed flux-concentrating TFPM machine with the configuration of single-sided, single winding, racetrack-shaped windings, claw poles, multiple-modules and multiple-slots per phase. In Figure 3-3 the claw pole cores with blue lines are showing the stator cores. In order to shorten flux paths, a multiple-module configuration with multiple-slots per phase [Ban 2008a] is used. The yellow racetrack-shaped structure represents the copper winding. The blue hexahedra with black arrows represent the permanent magnets (PMs), and the white hexahedra between the PMs represent the flux-concentrating cores in the rotor.

In order to facilitate manufacturing of the rotor with magnets and iron cores, a new configuration of magnets and iron cores is proposed in Figure 3-4. The parts with grey colour in Figure 3-4 are non-ferromagnetic parts to assemble magnets and iron cores. The configuration in Figure 3-3 is modified to the configuration segmented as Figure 3-4(a). The magnet and iron core segments are rearranged as in Figure 3-4(b). This new configuration allows for an increase in the volume of magnets while maintaining the pole pitch length without increasing the height of the iron cores as shown in Figure 3-4(c). In order to facilitate manufacture and assembly of magnets and iron cores, the configuration in Figure 3-4(d) is proposed as an alternative assembling method, using bolting. The non-ferromagnetic parts in Figure 3-4(d) can be made easily by the extrusion or the drawing method in manufacturing. Therefore, this configuration makes easier mass-production of flux-concentrating TFPM machines. The configuration proposed in Figure 3-4 can also be used for longitudinal flux PM machines.

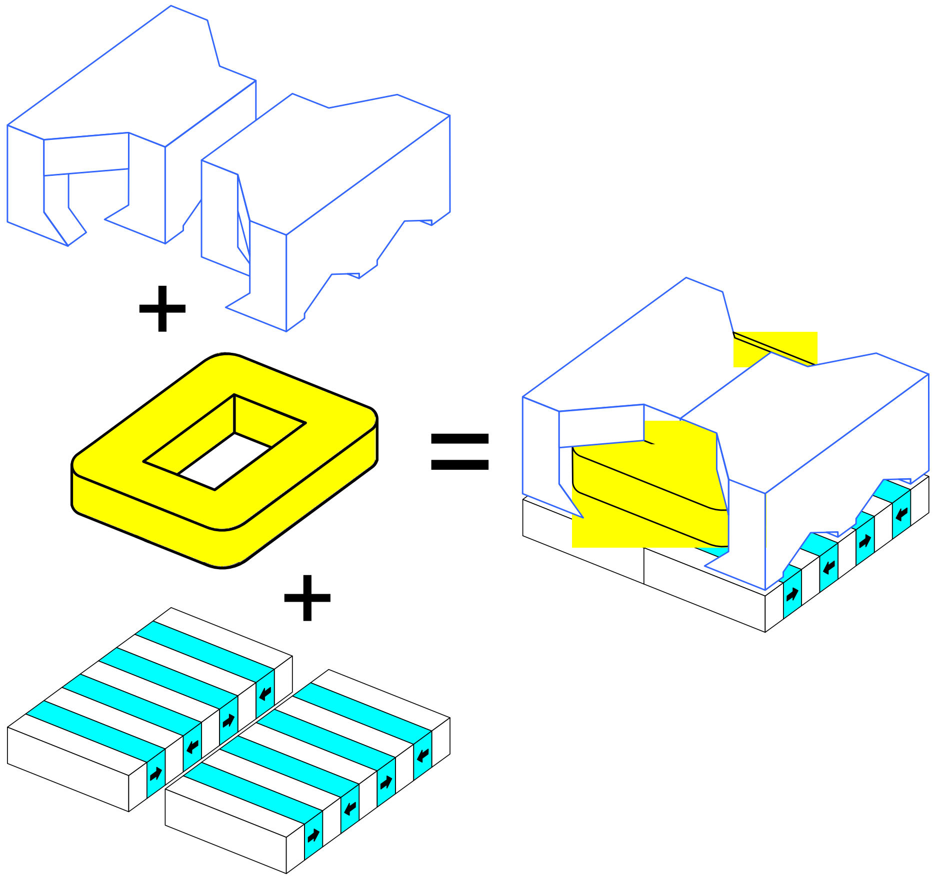


Figure 3-3: *New TFPM machine with flux-concentrating configuration*

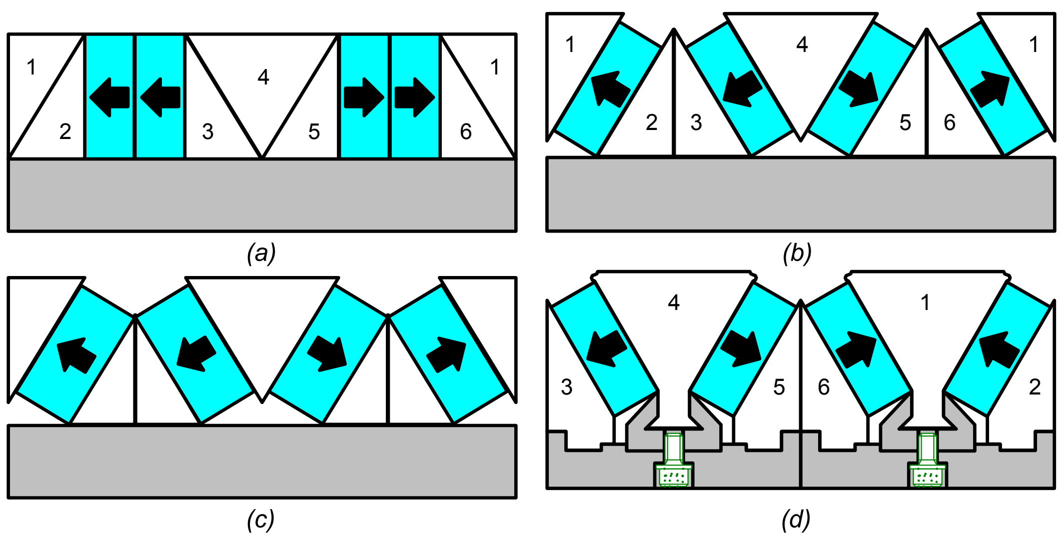


Figure 3-4: *New PMs and iron cores configuration of the flux-concentrating TFPM machine*

3.2 Analytical modelling of TFPM generator with multiple-modules

A sketch of the proposed TFPM generator with two slots per phase is illustrated in Figure 3-5. Figure 3-6 depicts the tangential and axial views of the generator with dimensional parameters.

The dotted lines in Figure 3-6 represent the main flux paths produced by the PM magneto-motive force. The electromagnetic dimensions and parameters of the proposed TFPM generator are determined by TABLE 2 in the report, D 1B2.b.4.

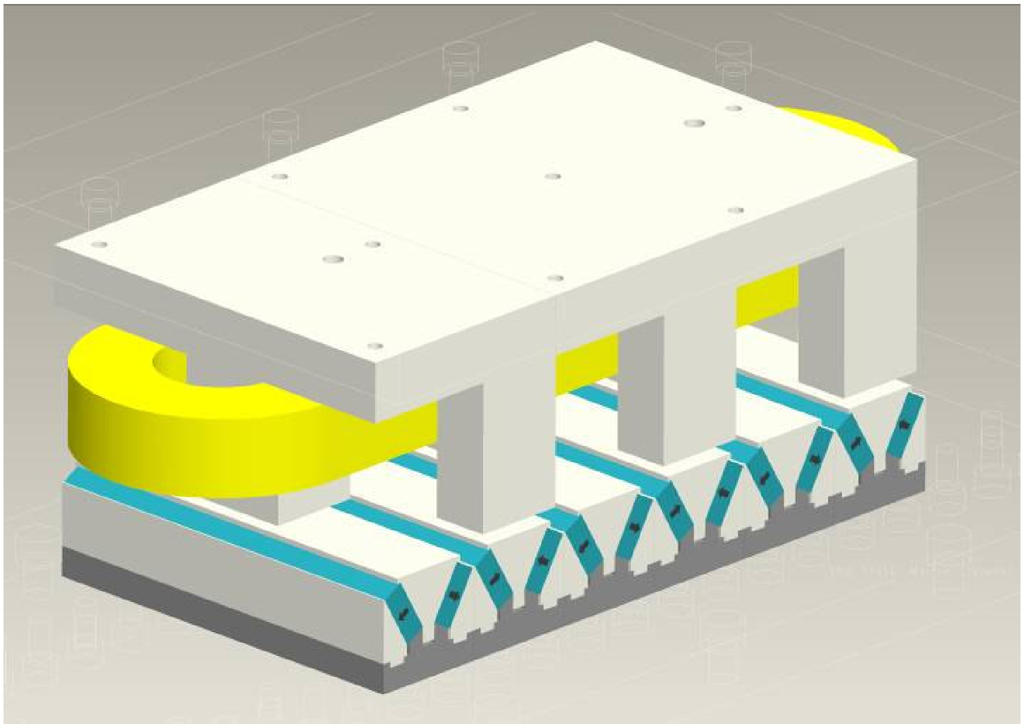
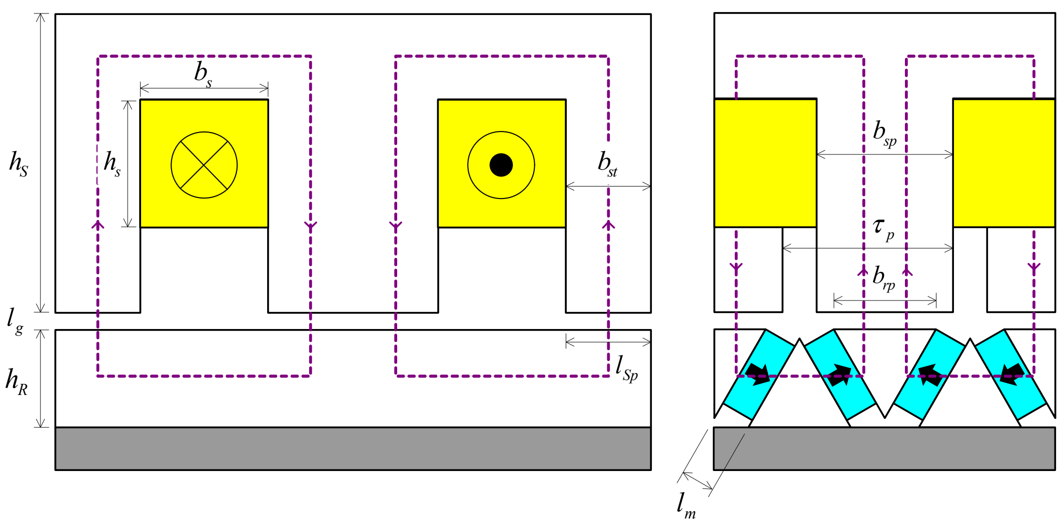


Figure 3-5: *3D sketch of multiple-module TFPM generator with two slots per phase*



(a) Cross-section in tangential view *(b) Cross-section in axial view*

Figure 3-6: *Cross-section view of multiple-module TFPM generator with two slots per a phase*

Electromagnetic reluctances in every pole pair are the same and repetitive. Electromagnetic reluctances in a pole are symmetrical with the reluctances in the next pole. Therefore, the equivalent circuit of electromagnetic reluctances in one pole is considered for the analytical model. Figure 3-7 illustrates the equivalent circuits of the reluctance model of the TFPM generator. The white rectangles represent iron core reluctances, and the white rectangles with bold lines represent air gap reluctances. The blue rectangles hatched represent PM reluctances and the red rectangles dotted represent leakage flux reluctances. In order to formulate the flux equations of the equivalent circuit in Figure 3-7, the equivalent circuit is modified as in Figure 3-8. The flux densities, the flux, the flux linkages in the air gap, the PM and the iron cores are determined by the calculation procedure described in the last chapter.

In order to determine the fluxes ϕ_A, ϕ_B, ϕ_C, ϕ_D, ϕ_E, ϕ_F, ϕ_G, ϕ_H, ϕ_I, ϕ_J, ϕ_K, and ϕ_L in Figure 3-8(a), Kirchhoff's voltage law is applied to the fluxes Φ_1, Φ_2, Φ_3, Φ_4 and Φ_5 in Figure 3-8(b), (c), (d) and (e).

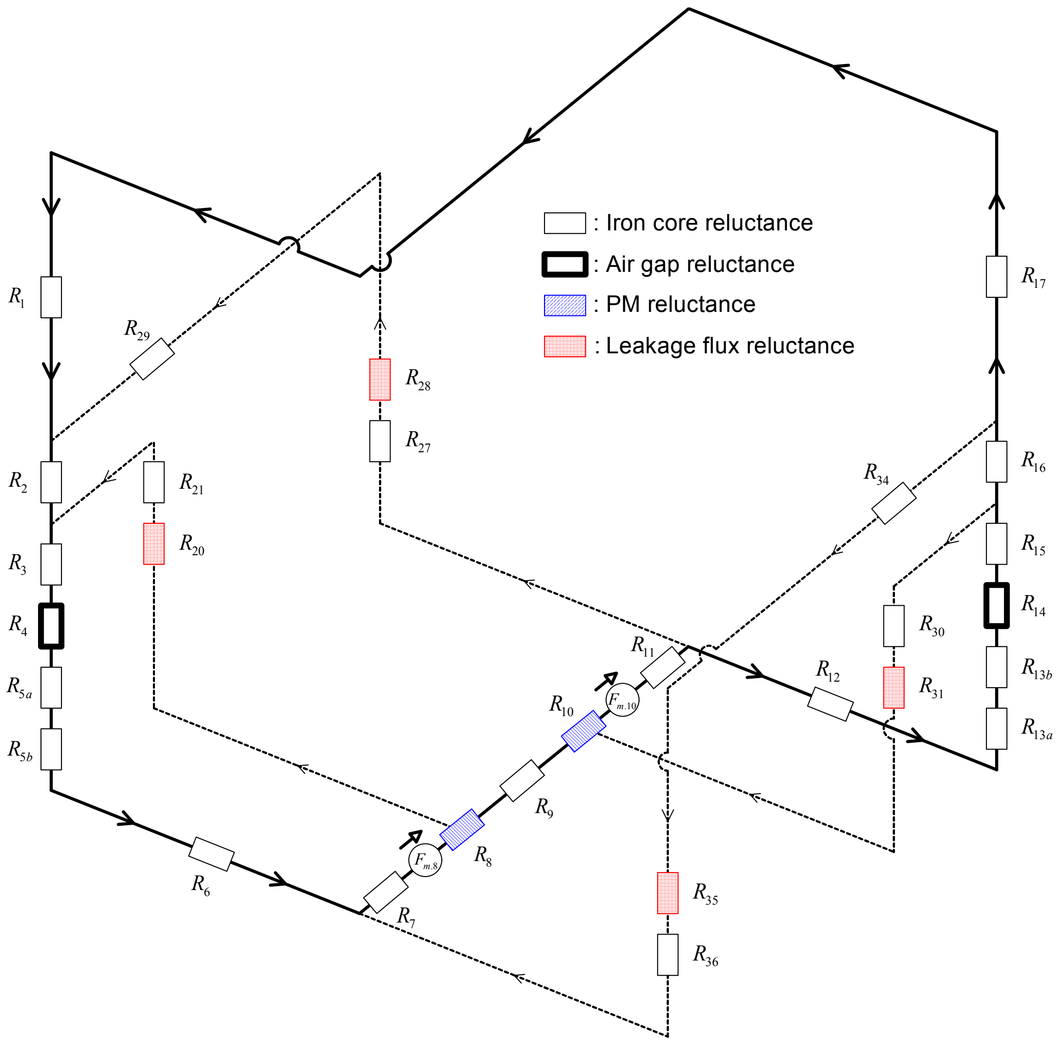
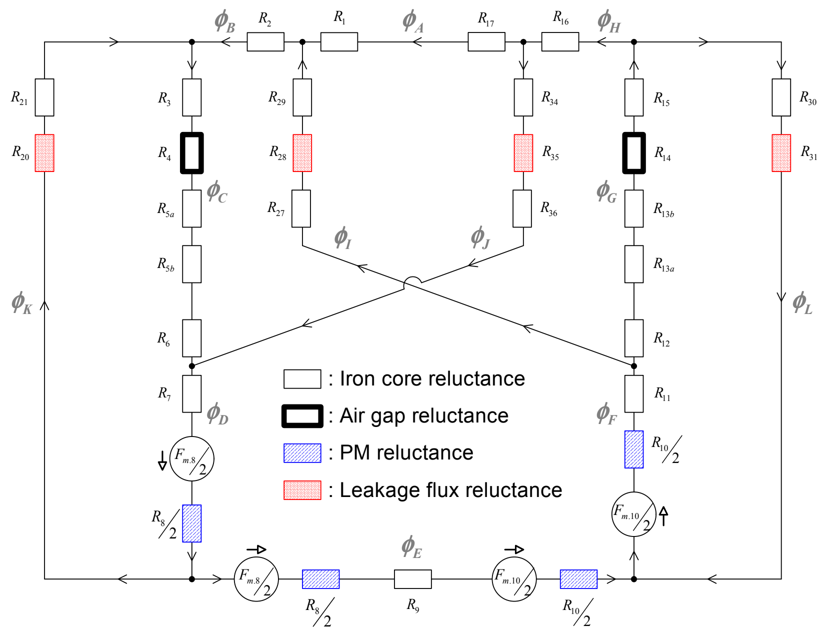
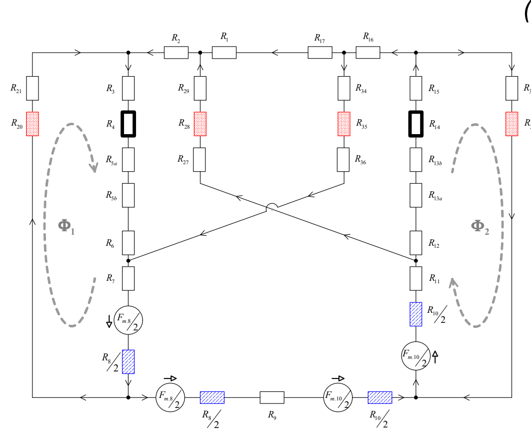


Figure 3-7: *Equivalent circuit of magnetic reluctances of the proposed TFPM generator*



(a)



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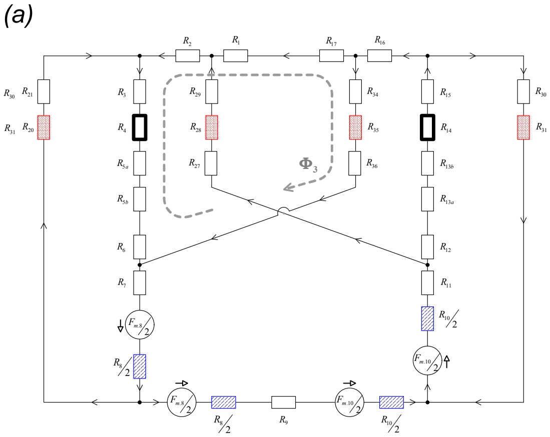
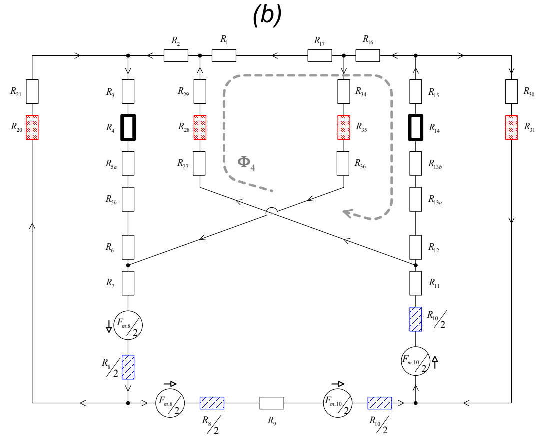
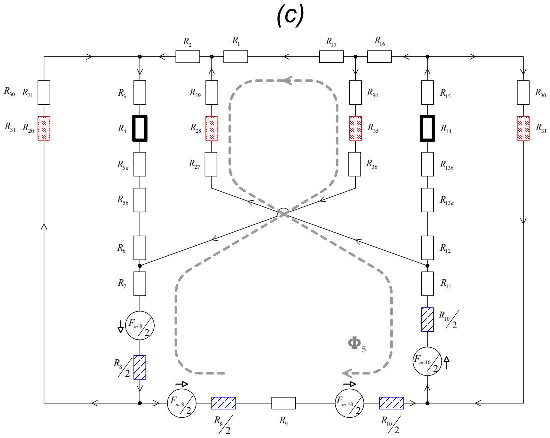


(c)



(d)



(e)

Figure 3-8: *Modified equivalent circuit of magnetic reluctances of the proposed TFPM generator*

3.3 Verification of magnetic circuit analysis model

This section discusses the verification of the magnetic circuit analysis model discussed in the last section. To verify the analysis model at no-load, the no-load induced voltage obtained through the analysis model is compared with the no-load voltage obtained through the measurement of a downscaled TFPM generator. To validate the analysis model at a load, the force of the generator obtained through the analysis model is compared with the force obtained through the static force measurement. The electromagnetic dimensions and parameters of the downscaled TFPM generator are given in TABLE 3-1. These dimensions and parameters were determined by TABLE 2 in the report, D 1B2.b.4. Material characteristics of the TFPM generator are given in TABLE 3-2.

TABLE 3-1
ELECTROMAGNETIC DIMENSIONS AND PARAMETERS OF DOWNSCALED TFPM GENERATOR WITH MULTIPLE-MODULES

Air gap length, l_g	4 [mm]
Pole pitch, τ_p	40 [mm]
Magnet height, l_m	8 [mm]
Stator pole width, b_p	32 [mm]
Rotor pole width, b_{pr}	24 [mm]
Number of conductors per slot, N_{cslot}	576 [Turn]
Stator slot width, b_s	30 [mm]
Stator slot height, h_s	30 [mm]
Number of pole pairs, p	40 [-]
Stator pole length, l_{sp}	20 [mm]
Stator height, h_S	70 [mm]
Stator yoke height, h_{sy}	20 [mm]
Rotor height, h_R	20 [mm]

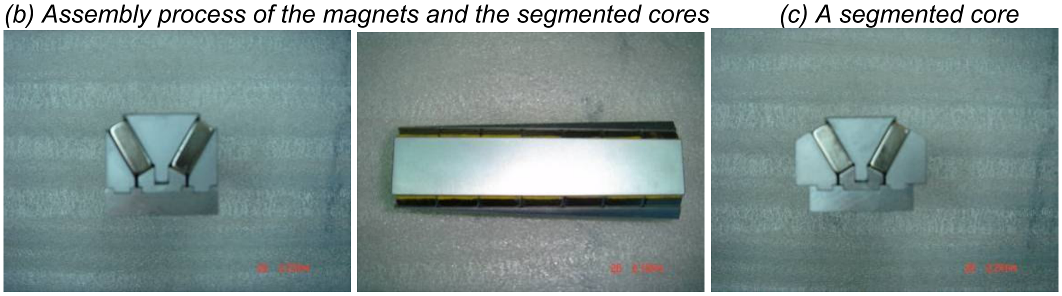
TABLE 3-2
MATERIAL CHARACTERISTICS OF TFPM MACHINE

Iron core type		Solid core (S20c)
Resistivity of copper, ρ_{Cu}		0.025 [μΩm]
Remanent flux density of permanent magnets, B_{rm}		1.2 [T]
Relative recoil permeability of permanent magnets, μ_{rm}		1.05 [-]
Permeability of free space, μ_0		$4\pi \times 10^{-7}$ [H/m]
Density	Iron core, ρ_{Fe}	7800 [kg/m^3]
	Permanent magnet, ρ_{pm}	7600 [kg/m^3]
	Copper, ρ_{Cumass}	8900 [kg/m^3]

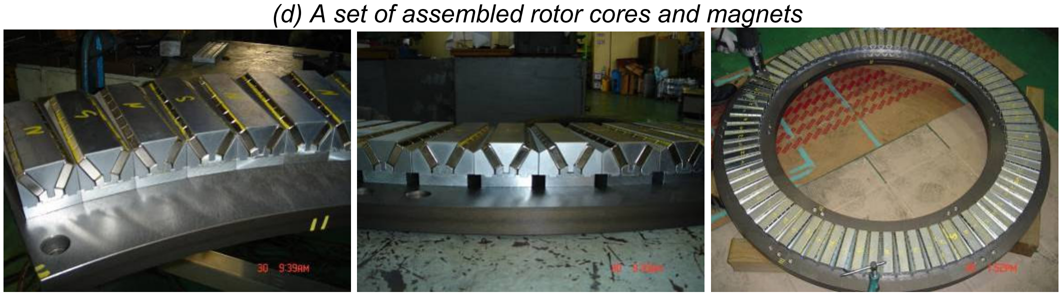
The downscaled TFPM generator, that was financially and technically supported by the Wintech Co., Ltd. in Korea, was built as in Figure 3-9, Figure 3-10 and Figure 3-11. The generator consists of multiple-sets of the stator and rotor. Considering easier manufacturing of the generator, a solid iron core is used to construct both the stator and the rotor.
Figure 3-9 depicts segmented rotor cores and magnets, an assembly process of the cores and magnets, and a set of assembled rotor. Figure 3-10 depicts a set of stator core, a racetrack-shaped winding, and a set of assembled stator. Figure 3-11 depicts the TFPM generator with structural components, rotor and stator sets.

(a) Segmented cores with an aluminium plate for assembly

(b) Assembly process of the magnets and the segmented cores *(c) A segmented core*



(d) A set of assembled rotor cores and magnets



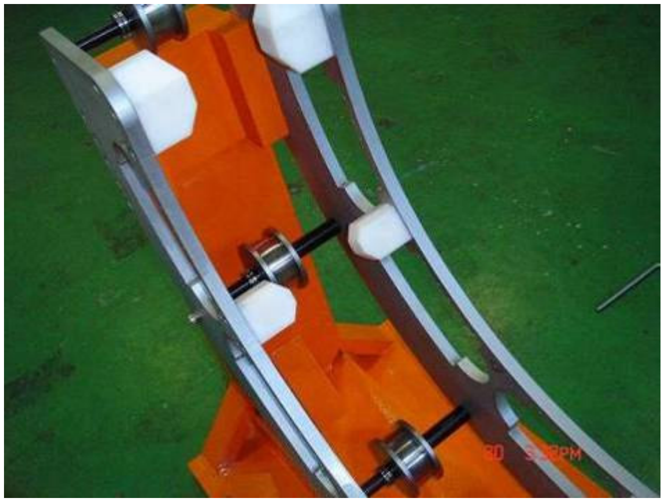
(e) Assembly process of the rotor

Figure 3-9: *Rotor cores and magnets with segmented construction of the proposed TFPM generator (supported by Wintech Co., Ltd. in Korea)*


(a) Stator core *(b) Racetrack-shaped copper winding*

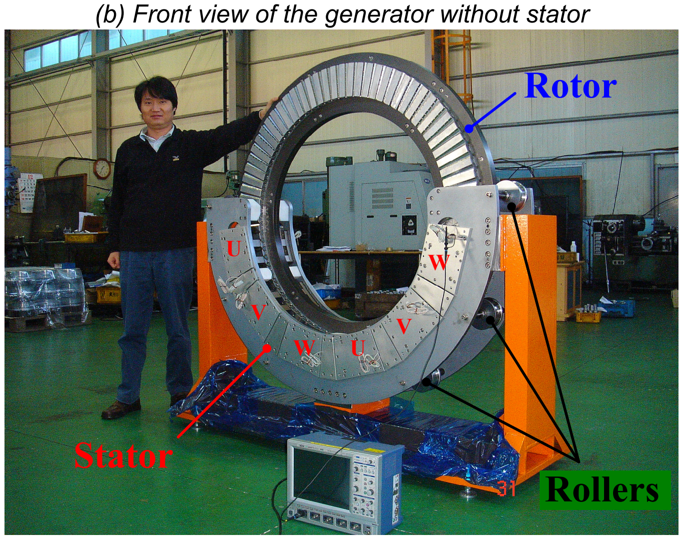
(c) A set of assembled stator

Figure 3-10: *The set of stator cores and racetrack-shaped winding of the proposed TFPM generator (supported by Wintech Co., Ltd. in Korea)*



(a) Structural components with rollers

(b) Front view of the generator without stator



(c) Generator with rotor and stator

Figure 3-11: *Proposed generator with sets of rotor and stator (supported by Wintech Co., Ltd. in Korea)*

3.3.1 Verification of no-load case

A. Analytical results

The peak flux density and the peak no-load voltage at 0.25 m/s air-gap speed by the analysis model of the TFPM generator are given in TABLE 3-3.

TABLE 3-3
PEAK FLUX DENSITY AND PEAK NO-LOAD INDUCED VOLTAGE OF THE DOWNSCALED TFPM GENERATOR WITH MULTIPLE-MODULES BY ANALYTICAL MODEL

Flux density in the stator core, $\hat{B}_p$	1.06 [T] at 2 [mm] air gap 0.93 [T] at 4 [mm] air gap
No-load induced voltage per two pole pairs, $\hat{e}_{2pole\_pair}$	28.21 [V] at 2 [mm] air gap 18.96 [V] at 4 [mm] air gap

B. Experimental results

Figure 3-12 depicts the experimental setup of the downscaled generator. The TFPM generator is driven by a motor drive set integrated into a gearbox. The specifications of the experimental setup are given in TABLE 3-4.

TABLE 3-4
SPECIFICATIONS OF EXPERIMENTAL SETUP

Driving motor	- 3 phase, AC machine - Nominal power: 14.3 [kW] - Nominal speed: 2,600 [rpm] - Nominal torque: 52.7 [Nm]
Pulley & belt	- 1st pulley diameter: 152.4 [mm] - 2nd pulley diameter: 304.8 [mm]
Gearbox	43:1 gear ratio
Generator diameter	- Outer diameter: 1.3 [m] - Inner diameter: 1 [m]
Air gap length	2 & 4 [mm]

Figure 3-13 depicts the measured no-load voltages of three phases at 4 mm air gap and at 0.25 m/s air gap speed. TABLE 3-5 gives the peak values of no-load voltages measured at 2 mm and 4 mm air gap and 0.25 m/s air gap speed.

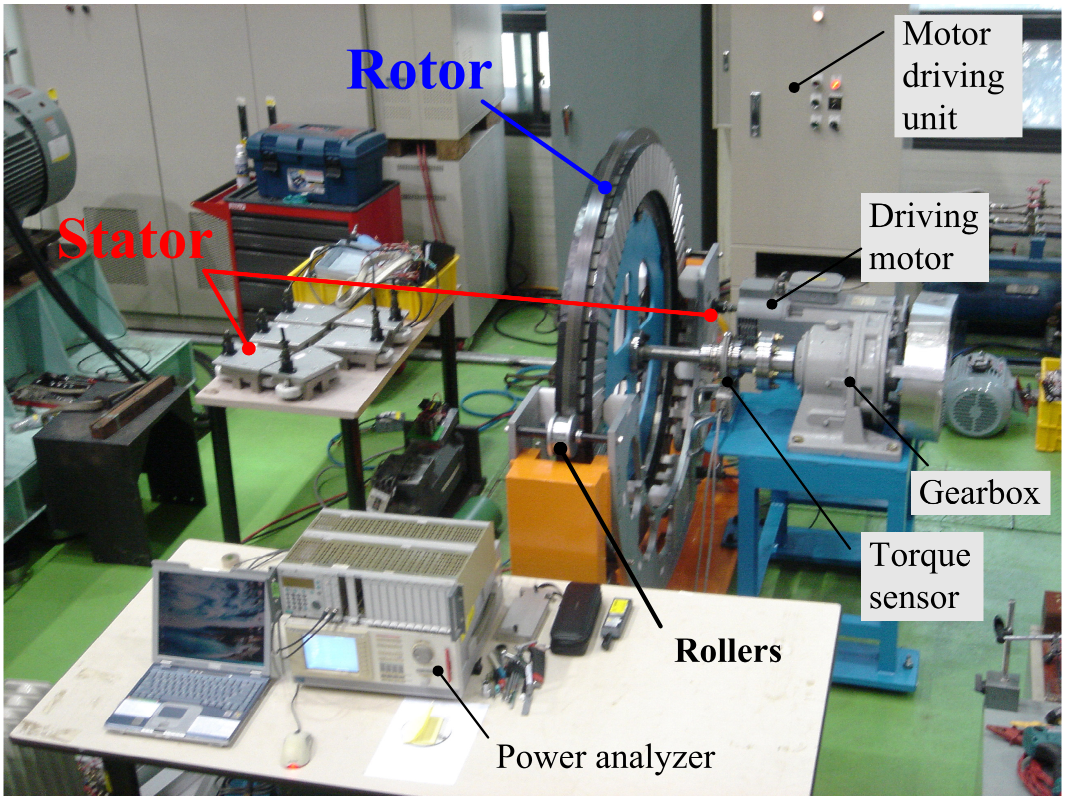


Figure 3-12: *Proposed TFPM generator with experimental setup*

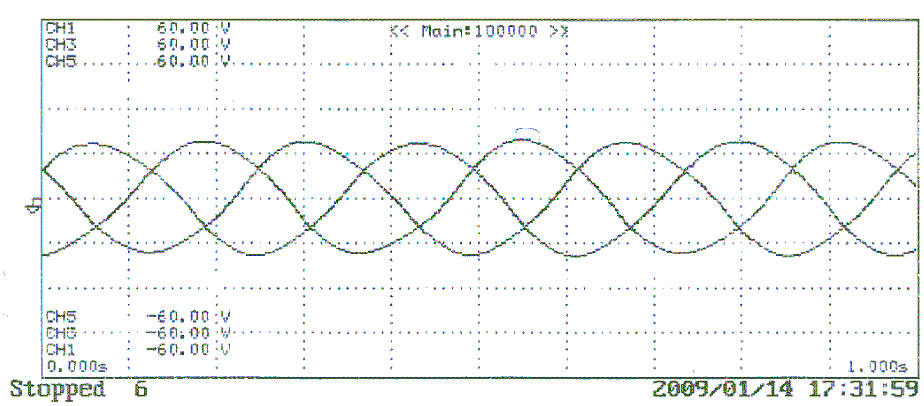


Figure 3-13: *No-load induced voltages measured at 0.25 m/s*

TABLE 3-5
PEAK NO-LOAD INDUCED VOLTAGE OF THE DOWNSCALED TFPM GENERATOR WITH MULTIPLE-MODULES BY MEASUREMENTS

No-load induced voltage per two pole pairs, $\hat{e}_{2pole\_pair}$	27.93 [V] at 2 [mm] air gap 18.73 [V] at 4 [mm] air gap

The peak no-load voltages of the generator with 2 [mm] and 4 [mm] air gap length measured at 0.25 [m/s] air gap speed are 1 [%] and 1.2 [%] lower than the voltages obtained through the analysis model. Therefore, the analysis model of the proposed TFPM generator is used for the design of the generator for large direct-drive wind turbines in the next section.

3.3.2 Verification in the case with a load

In order to validate the analysis model of the proposed TFPM generator with a load, the force obtained through the analysis model is compared with the force obtained from static force measurements. Using a force equation (30) in the report, D 1B2.b.4, the force of the proposed TFPM generator is calculated.
To measure the thrust force of the proposed TFPM generator, a linearized type of the generator is built and equipped on a test bench as shown in Figure 3-14. Figure 3-15 depicts the mearsued thrust force per pole pair of the generator as a function of the rotor displacement. Due to the effect of the cogging force and the reluctance force, the sinusoidal distribution of the thrust force was distorted as shown in Figure 3-15. Figure 3-16 depicts the differences between the thrust force obtained through the static force measurements and the force obtained through the analytical model. In Figure 3-16, it is indicated that the peak force measured at 25 % and 50 % of the nominal current is 5 % and 11 % lower than that obtained through the analytical model. During the static force measurements, it was not able to increase the current more than 50 % of the nominal current because of the current capacity limitation of the power supply.

Figure 3-14: *Proposed TFPM generator equipped on a test bench to measure the static force*

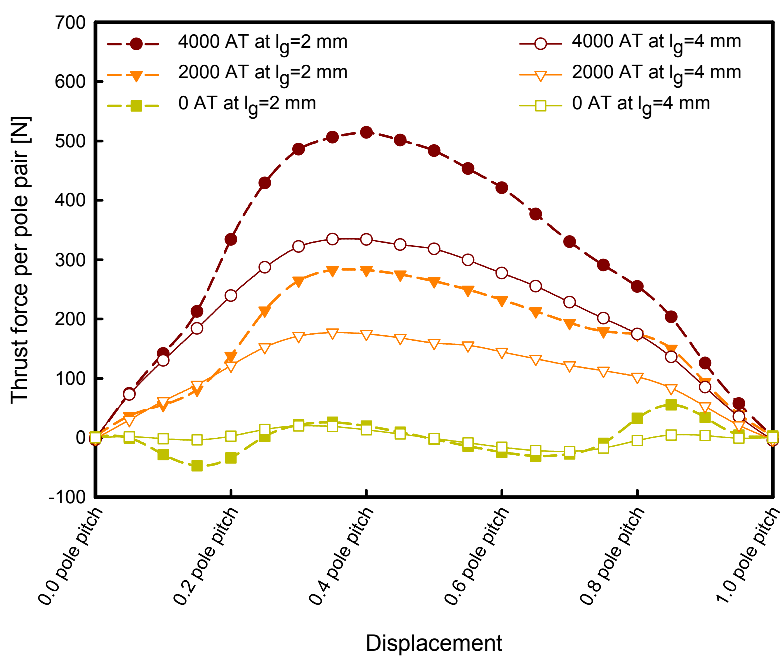


Figure 3-15: *Thrust force per a pole pair of the proposed TFPM generator by the measurement*

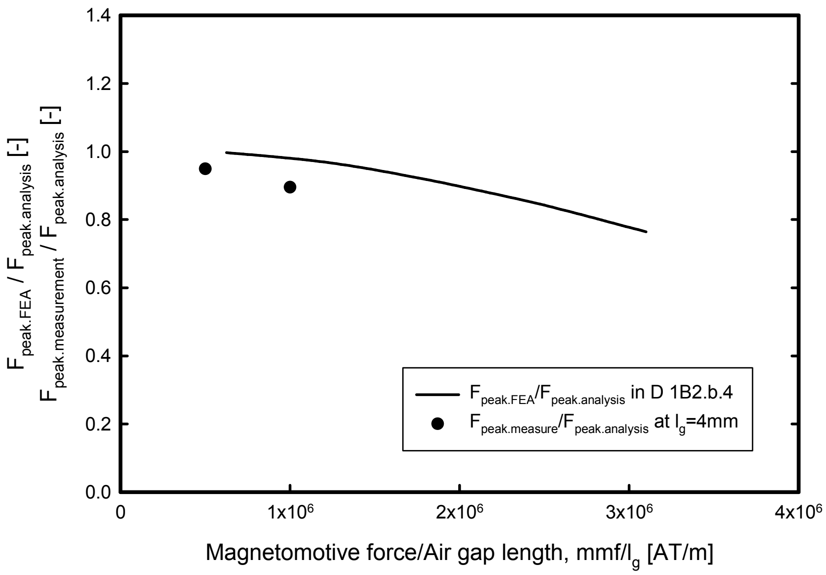


Figure 3-16: *Thrust force differences between the measurement and the analysis*

3.4 Design of TFPM generators with multiple-modules for large direct-drive wind turbines

Using the formulations and the analytical models derived in the last section, the proposed TFPM generator with multiple-modules and multiple-slots per phase is designed for 5 MW and 10 MW direct-drive wind turbines in this section. In the design the number of slot per phase is variable as 1, 2, 4 and 8. The TFPM generators designed with various numbers of slots per phase are assessed based on active mass, cost, loss, efficiency and force density. Design results of the generators are also compared with a surface-mounted RFPM generator and a flux-concentrating TFPM generator, namely the ***RFPMG*** and the ***TFPMG-U*** discussed in the last chapter.

Wind turbine parameters and generator requirements for 5 MW and 10 MW wind turbines are given in TABLE 3-6. In the design of the TFPM generators with multiple-modules, material characteristics and cost models used for the generators are given in TABLE 3-7.

TABLE 3-6
WIND TURBINE PARAMETERS AND GENERATOR REQUIREMENTS

Wind turbine parameters		
Rated grid power, P	5 [MW]	10 [MW]
Rotor blade diameter, D_r	126 [m]	178 [m]
Rotor blade tip speed, v_{tip}	80 [m/s]	80 [m/s]
Rated rotor speed, N	12.1 [rpm]	8.6 [rpm]
Generator requirements		
Nominal power, P_{gennom}	5.56 [MW]	11.12 [MW]
Nominal torque, T_{gennom}	4.38 [MNm]	12.38 [MNm]

TABLE 3-7
MATERIAL CHARACTERISTICS AND COST MODELS FOR GENERATOR

Material characteristics		
Specific hysteresis losses of iron cores	SMC core (Somaloy 700)	7.93 [W/kg] at 1.3 [T] and 50 [Hz]
Specific eddy current losses of iron cores,	SMC core (Somaloy 700)	0.17 [W/kg] at 1.3 [T] and 50 [Hz]
Resistivity of copper, ρ_{Cu}		0.025 [μΩm]
Remanent flux density of permanent magnets, B_{rm}		1.2 [T]
Relative recoil permeability of permanent magnets, μ_{rm}		1.05 [-]
Permeability of free space, μ_0		$4\pi \times 10^{-7}$ [H/m]
Density	Iron core, ρ_{Fe}	SMC core: 7440 [kg/m^3]
	Permanent magnet, ρ_{pm}	7600 [kg/m^3]
	Copper, ρ_{Cumass}	8900 [kg/m^3]
Cost models		
Iron core cost, k_{Fe}		3 [€/kg]
Copper cost, k_{Cus}		15 [€/kg]
Permanent magnet cost, k_{pm}		25 [€/kg]

In the analytical design for the proposed generator, the following parameters are used as input parameters.

(1) nominal power, P_{gennom} [MW]
(2) rotational speed, N [rpm]
(3) number of phases, m_{ph} [-]
(4) power factor, $\cos\phi$ [-]
(5) diameter of rotor, D_g [m]
(6) nominal current, I_s [A]
(7) RMS value of no-load voltage, e_p [V]
(8) current density, J_s [A/mm^2]
(9) slot filling factor of stator conductors, k_{sfill} [-]
(10) remanent flux density of permanent magnets, B_{rm} [T]
(11) relative recoil permeability of permanent magnets, μ_{rm} [-]

(12) permeability of free space, μ_0 [H/m]
(13) B-H curve data of iron cores
(14) axial length per three phases, l_s [mm]
(15) number of slots per phase, m_{module} [-]
(16) width of stator tooth, b_t [mm]
(17) height of stator yoke, h_{sy} [mm]
(18) length of stator pole, l_{sp} [mm]

Among the input parameters listed above, the values of the parameters from (1) to (13) are the same with the ***TFPMG-U***. Thus the parameters from (1) to (13) are kept constant in the design of the proposed TFPM generator. The parameter (14) axial length l_s is determined by two cases of assumptions in the design:

- Case-1: The axial length of the proposed TFPM generator is same as the axial length of the ***TFPMG-U***.
- Case-2: The pole area of the proposed TFPM generator is same as the pole area of the ***TFPMG-U***.

The parameter (15) number of slots per phase m_{module} is variable as 1, 2, 4 and 8. The parameters (16) width of stator tooth b_{st} and (17) height of stator yoke h_{sy} of the proposed TFPM generator are obtained by dividing b_{st} and h_{sy} of TFPMG-U with the number of slots per phase m_{module}. The parameter (18) length of stator pole l_{sp} is determined by 65 % [7][8]of the width of a stator module.
In the design procedure of the proposed generators under the limited design condition, the following geometric parameters are adjusted in order to obtain the required no-load induced voltage of the generators.

1. height of rotor, h_R [mm]
2. height of magnet, l_m [mm]

In the design of the proposed TFPM generator with multiple-modules and multiple-slots per phase, the following configurations of the generator are considered.

- ***TFPMG-CP/1/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited axial length (Case-1)
- ***TFPMG-CP/2/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited axial length (Case-1)
- ***TFPMG-CP/4/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited axial length (Case-1)
- ***TFPMG-CP/8/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited axial length (Case-1)
- ***TFPMG-CP/1/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited pole area (Case-2)
- ***TFPMG-CP/2/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited pole area (Case-2)
- ***TFPMG-CP/4/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited pole area (Case-2)
- ***TFPMG-CP/8/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited pole area (Case-2)

In order to identify the competitiveness of the proposed TFPM generators listed above, the design results of the generators are compared with the results of the following PM generators discussed in the last chapter.

- ***RFPMG***: a surface-mounted TFPM generator with full pitch windings
- ***TFPMG-U***: a single-sided, single winding flux-concentrating TFPM generator with a U-core

Figure 3-17 depict the external shape of the ten generators.

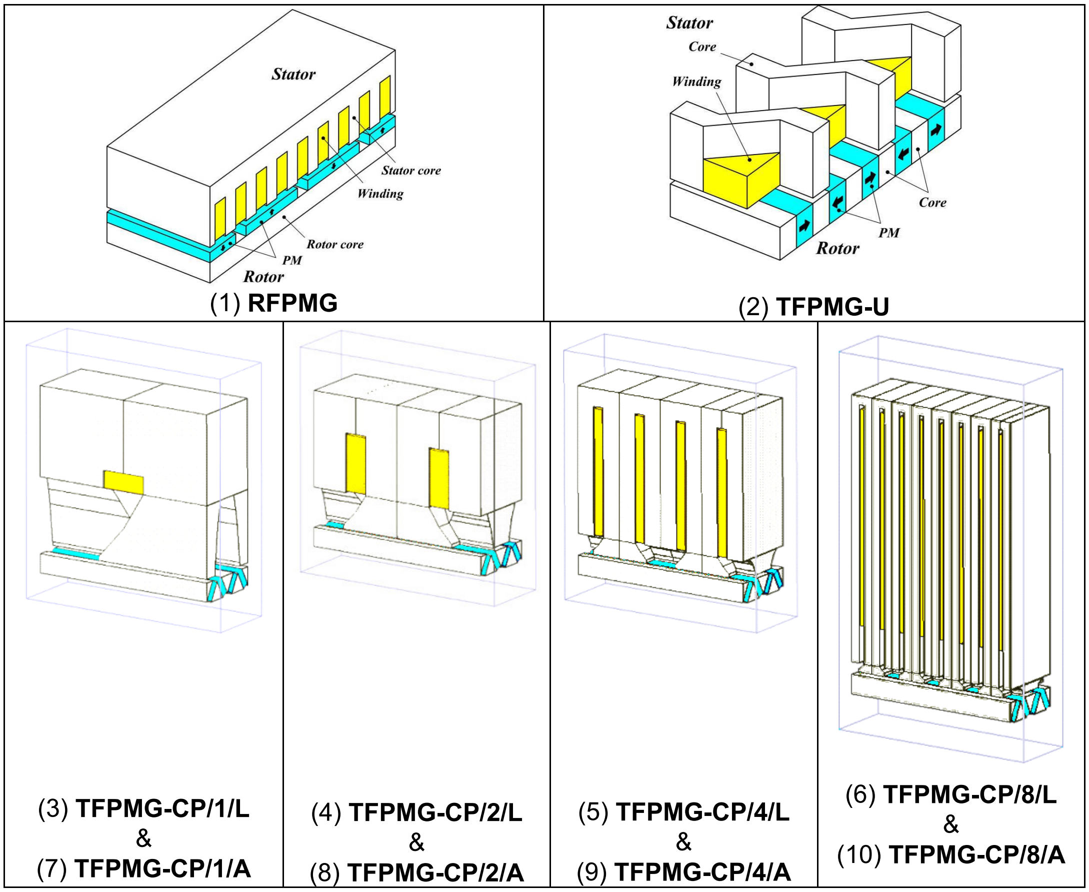


Figure 3-17: *External shapes of the ten PM generators*

TABLE 3-8 and TABLE 3-9 give the design results of parameters (15), (16), (17), (18) and (19) of the proposed 5 MW TFPM generators with limited axial length (Case-1) and limited pole area (Case-2), respectively. Design results of the parameters of the proposed 10 MW TFPM generators are given in TABLE 3-10 and TABLE 3-11. The electromagnetic dimensions and parameters of these TFPM generators were determined by TABLE 2 in the report, D 1B2.b.4.

TABLE 3-8

NUMBER OF SLOTS PER PHASE, WIDTH OF STATOR TOOTH, HEIGHT OF STATOR YOKE, LENGTH OF STATOR POLE OF 5 MW GENERATORS WITH LIMITED AXIAL LENGTH (CASE-1)

number of slot per phase, m_{module} [-]	1	2	4	8
axial length per three phases, l_s [m]	1.03	1.03	1.03	1.03
width of stator tooth, b_{st} [mm]	130.4	65.2	32.6	16.3
height of stator yoke, h_{sy} [mm]	130.4	65.2	32.6	16.3
length of stator pole, l_{sp} [mm]	223.2	111.6	55.8	27.9
height of rotor, h_R [mm]	33.8	33.8	34.7	36.8

TABLE 3-9

NUMBER OF SLOTS PER PHASE, WIDTH OF STATOR TOOTH, HEIGHT OF STATOR YOKE, LENGTH OF STATOR POLE OF 5 MW GENERATORS WITH LIMITED POLE AREA (CASE-2)

number of slot per phase, m_{module} [-]	1	2	4	8
axial length per three phases, l_s [m]	0.602	0.602	0.602	0.602
width of stator tooth, b_t [mm]	52.2	26.1	13.1	6.5
height of stator yoke, h_{sy} [mm]	52.2	26.1	13.1	6.5
length of stator pole, l_{sp} [mm]	130.4	65.2	32.6	16.3
height of rotor, h_R [mm]	111.8	114.5	126.2	173.0

TABLE 3-10

NUMBER OF SLOTS PER PHASE, WIDTH OF STATOR TOOTH, HEIGHT OF STATOR YOKE, LENGTH OF STATOR POLE OF 10 MW GENERATORS WITH LIMITED AXIAL LENGTH (CASE-1)

number of slot per phase, m_{module} [-]	1	2	4	8
axial length per three phases, l_s [m]	1.464	1.464	1.464	1.464
width of stator tooth, b_t [mm]	196.8	98.4	49.2	24.6
height of stator yoke, h_{sy} [mm]	196.8	98.4	49.2	24.6
length of stator pole, l_{sp} [mm]	317.2	158.6	79.3	39.7
height of rotor, h_R [mm]	49.4	49.2	50.2	52.7

TABLE 3-11

NUMBER OF SLOTS PER PHASE, WIDTH OF STATOR TOOTH, HEIGHT OF STATOR YOKE, LENGTH OF STATOR POLE OF 11 MW GENERATORS WITH LIMITED POLE AREA (CASE-2)

number of slot per phase, m_{module} [-]	1	2	4	8
axial length per three phases, l_s [m]	0.908	0.908	0.908	0.908
width of stator tooth, b_t [mm]	78.7	39.4	19.7	9.8
height of stator yoke, h_{sy} [mm]	78.7	39.4	19.7	9.8
length of stator pole, l_{sp} [mm]	196.8	98.4	49.2	24.6
height of rotor, h_R [mm]	194.5	196.4	237.0	240.0

Figure 3-18 depicts the active mass of ten different PM generators for 5 MW direct-drive wind turbines. In the figure, copper mass, iron core mass, magnet mass and total active mass are represented. Among the ten different PM generators, ***TFPMG-CP/1/A*** seems to be the lightest generator and ***TFPMG-CP/8/L*** seems to be the heaviest generator.

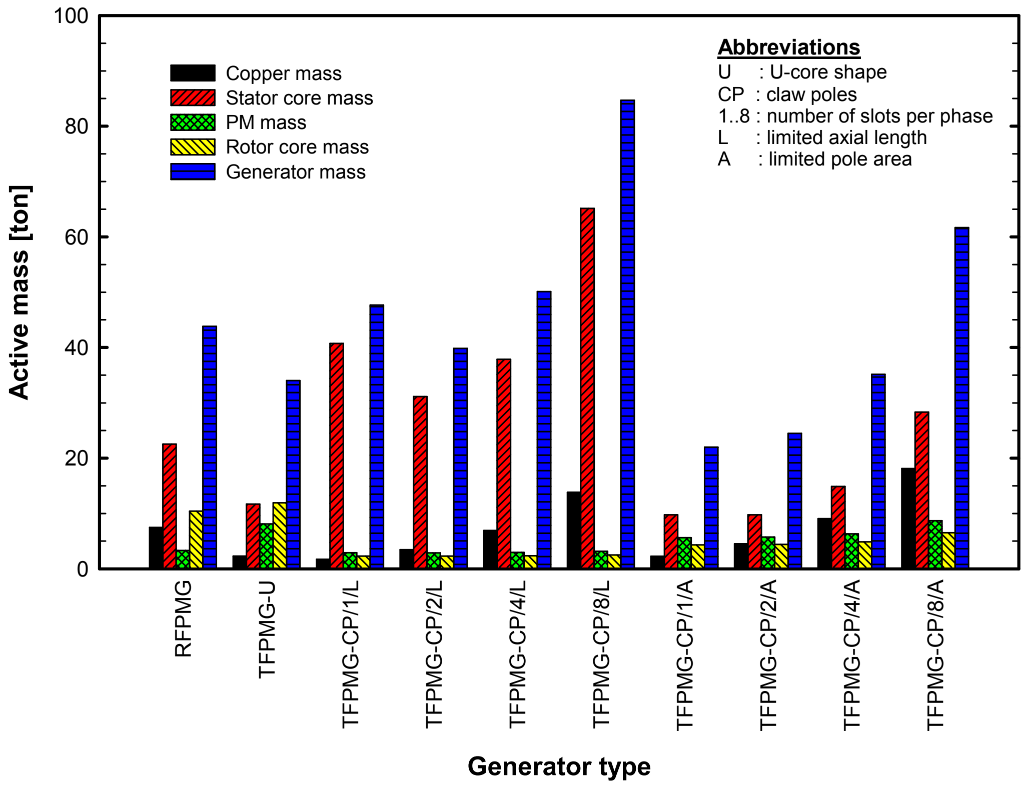


Figure 3-18: *Active mass of different PM generators for 5 MW direct-drive wind turbines*

Figure 3-19 depicts the competitiveness of the different PM generators in terms of efficiency, force density, cost and active mass. From the results, it is taken that ***TFPMG-CP/1/L*** has the highest efficiency (98.6 %) and ***TFPMG-CP/8/A*** has the lowest efficiency (90.2 %). The TFPM generators with claw poles and limited pole area have higher force density than the other generator. In terms of cost, ***TFPMG-CP/1/A*** seems cheaper than the other generators. ***TFPMG-CP/8/A*** seems to be the most expensive configuration.

Figure 3-20 depicts the active mass of the ten different PM generators for 10 MW direct-drive wind turbines. Among the ten different PM generators, ***TFPMG-CP/1/A*** and ***TFPMG-CP/2/A*** are addressed as the lightest generator and the second lightest generator, respectively. ***TFPMG-CP/8/L*** seems to be the heaviest generator.

Figure 3-21 depicts the competitiveness of different 10 MW PM generators in terms of efficiency, force density, cost and mass.

According to the results, ***TFPMG-CP/1/L*** seems to be the configuration with the highest efficiency and ***TFPMG-CP/8/A*** has the lowest efficiency. The TFPM generators with claw poles and limited pole area have higher force density than the other configurations. In terms of cost, ***TFPMG-CP/2/L*** has the highest competitiveness. ***TFPMG-CP/8/A*** seems to be the most expensive generator configuration.

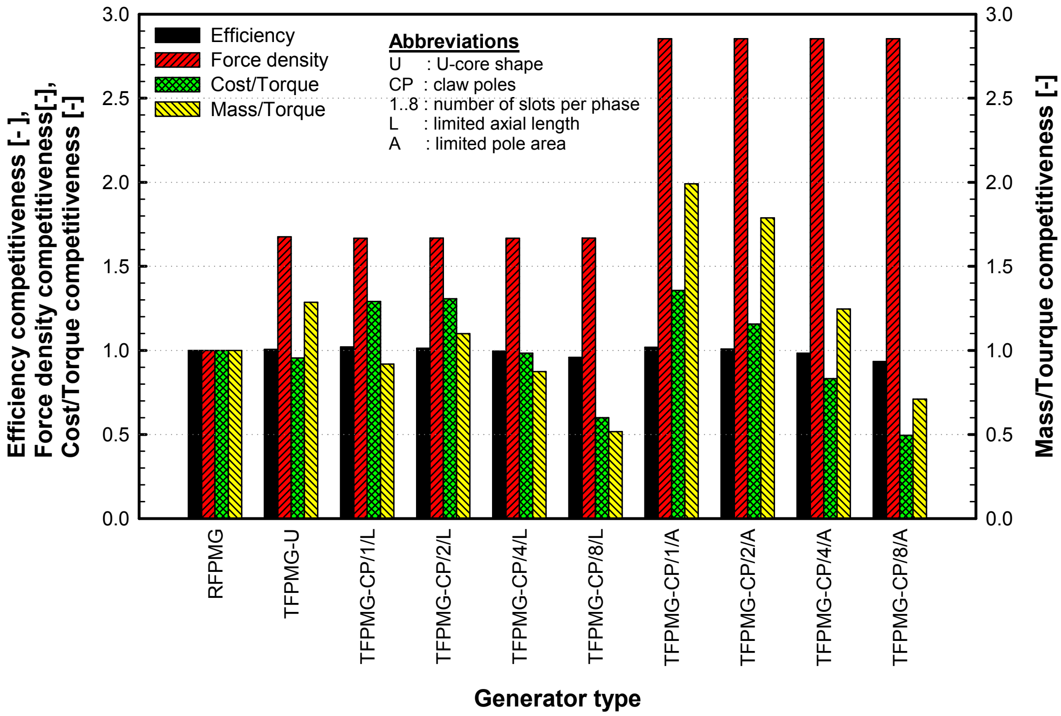


Figure 3-19: *Competitiveness of efficiency, force density, cost/torque ratio and mass/torque ratio of different PM generators for 5 MW direct-drive wind turbines*

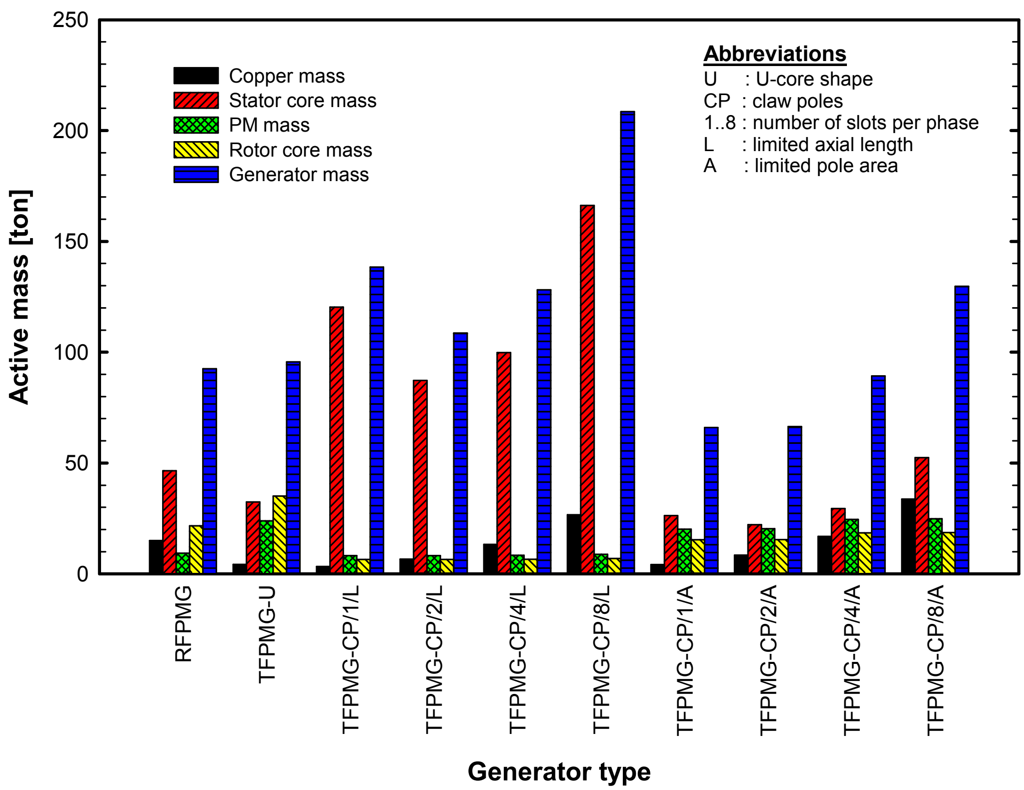


Figure 3-20: *Active mass of different PM generators for 10 MW direct-drive wind turbines*

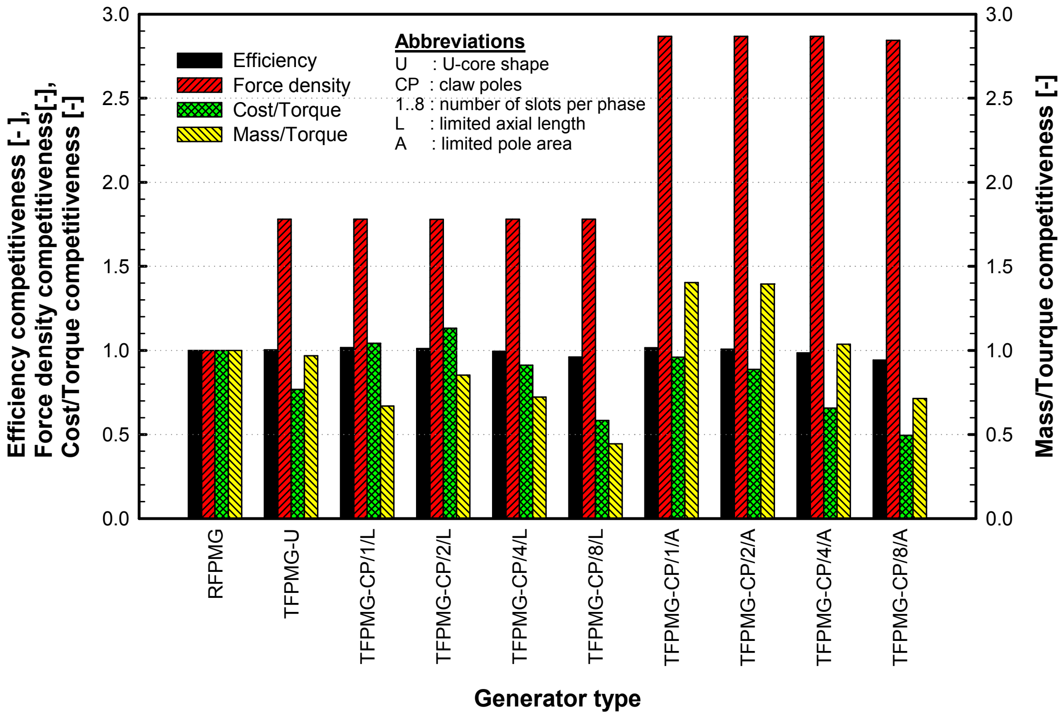


Figure 3-21: *Competitiveness of efficiency, force density, cost/torque ratio and mass/torque ratio of different PM generators for 10 MW direct-drive wind turbines*

TABLE 3-12 gives an overview of competitiveness of different 5 MW and 10 MW PM generators based on the criteria of active mass, cost, efficiency and force density. In the table, the generator with the highest competitiveness is indicated with "***9***", and the generator with the lowest competitiveness is indicated with "***0***".

TABLE 3-12
COMPARISON OF THE ELEVEN PM GENERATORS FOR 5 MW AND 10 MW DIRECT-DRIVE WIND TURBINES

		RFPMG	***TFPMG-U***	***TFPMG-CP/1/L***	***TFPMG-CP/2/L***	***TFPMG-CP/4/L***	***TFPMG-CP/8/L***	***TFPMG-CP/1/A***	***TFPMG-CP/2/A***	***TFPMG-CP/4/A***	***TFPMG-CP/8/A***
5 MW	Active mass	4	7	3	5	2	***0***	***9***	8	6	1
	Cost	5	3	7	8	4	1	***9***	6	2	***0***
	Efficiency	4	5	***9***	7	3	1	8	6	2	***0***
	Force density	0	5	2	3	1	4	***9***	***9***	***9***	***9***
10 MW	Active mass	6	5	1	4	3	***0***	***9***	8	7	2
	Cost	7	3	8	***9***	5	1	6	4	2	***0***
	Efficiency	4	5	***9***	7	3	1	8	6	2	*0*
	Force density	***0***	5	4	1	3	3	***9***	***9***	***9***	6

3.5 Conclusions

This chapter dealt with a new configuration of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance. A flux-concentrating transverse flux permanent magnet (TFPM) machine with multiple-modules segmented, multiple-slots per phase and racetrack-shaped copper windings was proposed to decrease the flux path length.

An analytical design model of the proposed TFPM generator was developed, and a downscaled TFPM generator was built to verify the analytical model. The no-load voltages measured at two different air gap lengths (2 mm and 4 mm) were 1 % to 1.2 % lower than the voltage obtained by the analytical model. To validate the analytical model in the case with a load, the force obtained by the analytical model was compared with the force obtained through measurement. The peak force measured at 25 % and 50 % of the nominal current was 5 % and 11 % lower than that obtained through the analytical model.

The analytical design model was used for the design of proposed TFPM generators for 5 MW and 10 MW direct-drive wind turbines. In the analytical design, the number of slots per phase was variable as 1, 2, 4 and 8. The TFPM generators designed with various numbers of slots per phase were assessed based on active mass, cost, loss, efficiency and force density.

The following ten different PM generator configurations were discussed in the analytical design.

- ***RFPMG***: a surface-mounted TFPM generator with full pitch windings
- ***TFPMG-U***: a single-sided, single winding flux-concentrating TFPM generator with a U-core
- ***TFPMG-CP/1/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited axial length
- ***TFPMG-CP/2/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited axial length
- ***TFPMG-CP/4/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited axial length
- ***TFPMG-CP/8/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited axial length
- ***TFPMG-CP/1/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited pole area
- ***TFPMG-CP/2/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited pole area
- ***TFPMG-CP/4/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited pole area
- ***TFPMG-CP/8/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited pole area

Among these different PM generators, ***TFPMG-CP/1/A*** was addressed as the lightest generator, ***TFPMG-CP/2/A*** was addressed as the second lightest generator and ***TFPMG-CP/8/L*** was addressed as the heaviest generator for 5 MW and 10 MW wind turbines. From the design of the generators for 5 MW wind turbines, it was taken that the active mass of ***TFPMG-U***, ***TFPMG-CP/2/L***, ***TFPMG-CP/1/A***, ***TFPMG-CP/2/A*** and ***TFPMG-CP/4/A*** are smaller than that of ***RFPMG***. The active mass of ***TFPMG-CP/1/A***, ***TFPMG-CP/2/A*** and ***TFPMG-CP/4/A*** seems to be lighter than that of ***RFPMG*** for 10 MW wind turbines.

In the chapter, the current density of the proposed TFPM generators was kept constant for various numbers of slots per phase. This represents the length of flux paths of the generators with large numbers of slots per phase was not shorter than the length of generators with small numbers of slots per phase. Therefore, the mass of the TFPM generator with eight slots per phase was larger than that of the generators with one slot per phase.

To reduce the length of flux paths further more, increasing current density would be an alternative. To increase current density, cooling effect of the machine must be also increased.

4. Conclusions and Recommendations

4.1 Conclusions

4.1.1 Comparison of PM generators for large direct-drive wind turbines

A comparative design of PM generators for large direct-drive wind turbines was represented to assess different configurations of the generators based on the active mass, losses and cost. The following five configurations of PM generators were selected for the comparative design.

- ***RFPMG****:* a surface-mounted RFPM generator with full pitch windings
- ***TFPMG-U****:* a single-sided, single winding flux-concentrating TFPM generator with a U-core
- ***TFPMG-C****:* a double-sided, single winding flux-concentrating TFPM generator with a C-core
- ***TFPMG-U/PR****:* a single-sided, single winding flux-concentrating TFPM generator with a U-core and passive rotor
- ***TFPMG-C/PR****:* a double-sided, single winding flux-concentrating TFPM generator with a C-core and passive rotor

Among the five different generators, the ***TFPMG-U*** was addressed as the lightest generator for 5 MW wind turbines. However, in the design of the generators for 10 MW wind turbines, the ***RFPMG*** was addressed as the lightest generator. The ***TFPMG-C*** had the smallest loss and the lowest cost compared to the other generators for both 5 MW and 10 MW turbines. The ***TFPMG-C/PR*** was addressed as the generator with the largest mass, the highest cost and the largest loss for both 5 MW and 10 MW turbines. The ***TFPMG-C/PR*** and ***TFPMG-U/PR*** were more expensive than the other generators, since both generators consist of large mass of permanent magnets which are the most expensive active material. The ***TFPMG-C*** and ***TFPMG-C/PR*** were more complicated in constructing because these two generators have double-sided air gaps. Therefore, the ***TFPMG-U*** was selected as a suitable generator for large direct-drive wind turbines.

In [3] it was concluded that the TFPM machine with toothed rotor was a valuable option in terms of the active mass and cost, if the air gap length can be kept below 1.5 mm. However, the design results in this chapter indicated that the conclusion in [3] is not valid for all configurations of flux-concentrating TFPM machines.

4.1.2 New configuration of TFPM generator for large direct-drive wind turbines

It was dealt to derive a new configuration of large direct-drive wind generators that would enable active mass reduction and facilitate manufacture and maintenance. A flux-concentrating transverse flux permanent magnet (TFPM) machine with multiple-modules segmented, multiple-slots per phase and racetrack-shaped copper windings was proposed to decrease the flux path length.

An analytical design model of the proposed TFPM generator was derived, and the model was verified by the experiment of a downscaled TFPM generator. Using the analytical design model, the proposed TFPM generators for 5 MW and 10 MW direct-drive wind turbines were designed and compared based on active mass, cost, loss, efficiency and force density. The following ten different PM generator configurations were discussed in the analytical design.

- ***RFPMG***: a surface-mounted TFPM generator with full pitch windings
- ***TFPMG-U***: a single-sided, single winding flux-concentrating TFPM generator with a U-core
- ***TFPMG-CP/1/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited axial length
- ***TFPMG-CP/2/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited axial length
- ***TFPMG-CP/4/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited axial length
- ***TFPMG-CP/8/L***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited axial length

- ***TFPMG-CP/1/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, one slot per phase and limited pole area
- ***TFPMG-CP/2/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, two slots per phase and limited pole area
- ***TFPMG-CP/4/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, four slots per phase and limited pole area
- ***TFPMG-CP/8/A***: single-sided, single winding flux-concentrating TFPM generator with claw poles, eight slots per phase and limited pole area

Among these different PM generators, ***TFPMG-CP/1/A*** was addressed as the lightest generator, ***TFPMG-CP/2/A*** was addressed as the second lightest generator and ***TFPMG-CP/8/L*** was addressed as the heaviest generator for 5 MW and 10 MW wind turbines. From the design of the generators for 5 MW wind turbines, it was taken that the active mass of ***TFPMG-U***, ***TFPMG-CP/2/L***, ***TFPMG-CP/1/A***, ***TFPMG-CP/2/A*** and ***TFPMG-CP/4/A*** are smaller than that of ***RFPMG***. The active mass of ***TFPMG-CP/1/A***, ***TFPMG-CP/2/A*** and ***TFPMG-CP/4/A*** seems to be lighter than that of ***RFPMG*** for 10 MW wind turbines.

4.2 Recommendations

4.2.1 Analytical model of TFPM generator

A generalized analytical model to use for various configurations of TFPM generators was proposed in a previous report, D 1B2.b.4. To improve the analytical model, the stator current may be included in further research.

4.2.2 Three-dimensional finite element analyses (3D FEA)

To validate PM generators for large direct-drive wind turbines, three-dimensional finite element analyses (3D FEA) are necessary in further research.

4.2.3 Disadvantages of TFPM generator

This report focused on finding a TFPM generator that would enable active mass reduction and facilitate manufacture and maintenance. Thus the disadvantages of the machine, low power factor and high cogging torque, were not discussed in this report. However, overcoming these disadvantages must be included in further research in order to strengthen the competitiveness of the machine.

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