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"Integrated Wind Turbine Design"

RESEARCH REPORT
on NUMERICAL EVALUATION of VARIOUS VARIABLE SPEED WIND GENERATOR SYSTEMS

(Deliverable No.: D 1B2.b.3)

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Abstract:

Based on the analytical design models of different wind generator systems (see in Report 1), this report surveys the most cost effective wind generator system by using the optimization method for the possible wind turbine drive-train concepts. Firstly, an improved genetic algorithm (IGA) as the optimization method is presented, which is demonstrated by the typical nonlinear mathematic functions and a 500-kW direct-drive PM generator system in literatures. Secondly, the characteristics of 7 types of variable speed constant frequency wind generator systems (PMSG_DD, PMSG_1G, PMSG_3G, EESG_DD, DFIG_3G, DFIG_1G and SCIG_3G) are introduced, and the optimization design models are developed, respectively. Finally, the optimization results are obtained for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10-MW, respectively. The numerical evaluations of various wind generator systems are presented.

Contents

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public			Private web site	
S1	Reviewed			**R1**	Restricted to project members			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

With rapid development of wind power technologies and significant growth of wind power capacity installed worldwide, various wind turbine concepts have been developed. The wind energy conversion system is demanded to be more cost-competitive, so that comparisons of different wind generator systems are necessary and imperative. This report investigates the numerical evaluation of possible wind generator systems by the design optimization. The analytical design models of different wind generator systems have been described in Report 1. Based the presented design models, the optimization models and the optimization results of the investigated wind generator systems are developed. The most cost-effective wind generator systems are analyzed. The obtained results of this report will make it interesting to wind generator manufactures and wind farm planning departments. The numerical evaluation may be helpful to make a judicious choice of the suitable wind generator systems.

1.1 Wind turbine specifications

1.1.1 Turbines characteristics

The following specifications of wind turbines are considered to investigate various wind generator systems in this study:

•Three blades

•Upwind

•Variable-pitch control

•Variable-speed operation with maximum power coefficient = 0.48

•Variable-speed operation with the optimum tip-speed ratio = 7.0

•Air density = 1.225 kg/m^3

•Turbine hub height = 1.2 times rotor diameter

•Annual average wind speed at the 10 m height = 7 m/s

•Weibull density distribution of wind speed and the shape parameter = 2

•Cut-in wind speed =2.5m/s

•Cut-out wind speed = 25m/s

1.1.2 Assessment sizes

With rapid development of wind power technologies, the size of wind turbines installed in the world is increasing. The annual average wind turbine size installed worldwide during 1996-2006 is presented in Fig. 1-1 [1]. It can be seen that the average size installed in 1996 was around 500 kW, and the average size in 2006 was over 1.5 MW which is three times larger than the size in 1996. In addition, the scale growth of single wind turbine on the market during 1980-2005 is also presented in Fig. 1-2 [2].

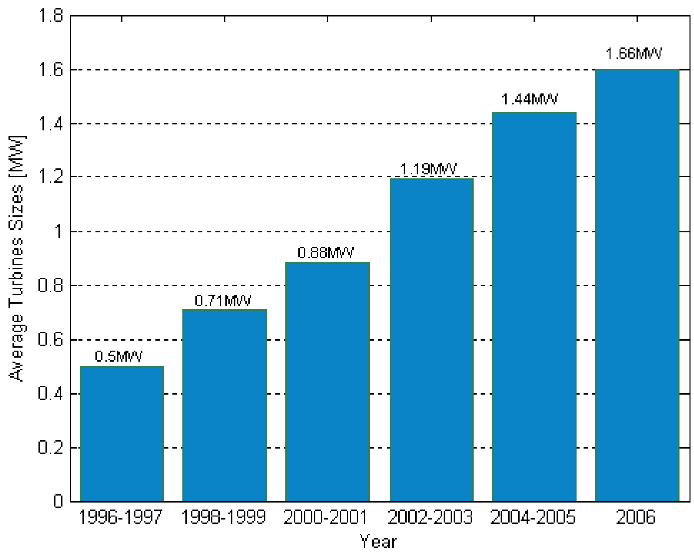


Fig. 1-1: *Annual average wind turbine size installed worldwide during 1996-2006*

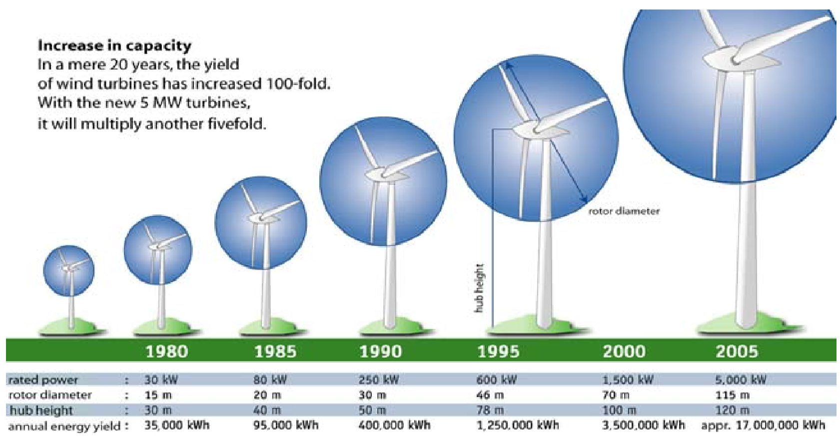


Fig. 1-2: *Development of power and size of wind turbines (Source: Bundesverband WindEnergie e.V.)*

In recent years, the rated powers in a range from 1MW to 3MW are popular on the currently markets. The rated power of the largest wind turbine on the market is almost 5-MW. Larger (offshore) wind turbines are currently being developed, it is reported that the rated power may be up to 10-MW in the future on the Europe markets [2-5]. In order to compare the performances of different wind generator systems in a certain size range, five power ratings of 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10-MW are investigated. Table 1-1 summarizes the specifications for the investigated wind turbines [1] [2] [5].

Table 1-1: *Wind turbine specifications*

Power rating [MW]	0.75	1.5	3.0	5.0	10.0

Rotor diameter [m]	50	70	90	115	170
Hub height [m]	60	84	108	138	204
Rated rotor speed [rpm]	28.6	20.5	16	14.8	10
Swept area [$\times10^3$ m^2]	1.96	3.85	6.36	10.4	22.7
Specific rating [kW/m^2]	0.38	0.39	0.47	0.48	0.44
Hub height annual mean wind speed [m/s] (for production estimates)	10.28	10.85	11.32	11.84	12.84

1.2 Wind generator systems configurations investigated

In various types of wind generators, permanent magnet (PM) machines appear more and more promising, because the advantages of PM machines over electrically excited machines are higher efficiency and energy yield, no additional power supply for the magnet field excitation and higher reliability due to the absence of mechanical components as slip rings. In addition, the performance of PM materials is improving and the cost of PM is decreasing in recent years [3-10]. Therefore, these advantages and trends may make direct-drive PM wind generator systems more attractive in application for large scale (offshore) wind turbines. In this report, including the direct-drive concepts, a single-stage and three-stage geared drive trains with PM generator are also analyzed. The following designs and comparison of seven different variable speed constant frequency wind turbine concepts are investigated during the study:

• Permanent magnet synchronous generator (PMSG) systems

(1) *PMSG_DD*: A wind turbine main shaft directly drives a low-speed, high-torque, PM excited synchronous generator.

(2) *PMSG_1G*: A single-stage gearbox drives a medium-speed, medium-torque, PM excited synchronous generator.

(3) *PMSG_3G*: A three-stage gearbox drives a high-speed, low-torque, PM excited synchronous generator.

All of the generator’s electrical output is processed and coupled to the utility grid by a full-rated power electronic (PE) system.

• Electrically Excited synchronous generator (EESG) systems

(4) *EESG_DD*: A wind turbine main shaft directly drives a low-speed, high-torque, EESG system. All of the generator’s electrical output is processed and coupled to the utility grid by a full-rated PE system.

• Doubly fed induction generator (DFIG) systems

(5) *DFIG_3G*: A three-stage gearbox driving a high-speed wound-rotor induction generator, the rotor power is processed and coupled to the utility grid by a PE system with a rating about one-third that of the generator.

(6) *DFIG_1G*: A single-stage gearbox driving a medium-speed, wound-rotor induction generator, the rotor power is processed and coupled to the utility grid by a PE system with a rating about one-third that of the generator.

• Squirrel cage induction generator (SCIG) systems

(7) *SCIG_3G*: A three-stage gearbox driving a high-speed SCIG system and the generator’s electrical output is interfaced to the utility grid with a full rated PE system.

Detailed descriptions of these drive trains are given in sections 2-5 of this report, which are devoted to their design and assessment, respectively. According to the drive train types, Table 1-2 depicts the outlines of the investigated wind generator systems.

Table 1-2: *Drive train configurations investigated*

Concept	Definition	Gearbox	Generator configurations	Abbreviation
Direct-drive	Low speed	None	PM synchronous	*PMSG_DD*
			Wound rotor synchronous	*EESG_DD*
Geared-drive	Medium speed	Single stage	PM synchronous	*PMSG_1G*
			Wound rotor induction	*DFIG_1G*
	High speed (1200rpm)	Three stage	PM synchronous	*PMSG_3G*
			Wound rotor induction	*DFIG_3G*
			Squirrel cage induction	*SCIG_3G*

1.3 Project approach

1.3.1 Comparison criteria

To make a numerical evaluation of various wind generator configurations, the design optimization is applied by the genetic algorithm for the minimum generator system cost. The electromagnetic design for each generator type is performed, and the analytical models have been presented in Report 1. The description of the used genetic algorithm will be introduced in subsection 1.3.2. The generator system cost includes the generator active material cost, the generator structural cost, the gearbox cost (if present), the PE cost and the other electrical subsystem cost, which includes transformer, cable, switchgear and so on. Table 1-3 depicts the components specifications of the investigated generator systems [3] [6] [8].

Table 1-3: *Generator system specifications*

Specific losses	
Losses percentage of rated power in a single-stage gearbox	1.5%
Losses percentage of rated power in a three-stage gearbox	3.0%
Hysteresis losses at 1.5T and 50Hz p_{Fe0h} [w/kg]	2
Eddy-current losses at 1.5T and 50Hz p_{Fe0e} [w/kg]	0.5
Converter losses percentage at the rated power k_c	3%
Specific cost	
Specific cost of a single-stage gearbox (Euro/kg)	6

Specific cost of a three-stage gearbox (Euro/kg)	10
A single-stage gearbox service factors F_s	1.25
Planet wheels number in a single–stage gearbox Z	6
Specific cost of laminated iron c_{Fe} [Euro/kg]	3
Specific cost of copper c_{cu} [Euro/kg]	15
Specific cost of NdFeB magnets c_m [Euro/kg]	40
Specific cost of a referenced generator structure c_{str} [kEuro]	15
Specific cost of power electronics c_{con} [Euro/kW]	40
Specific cost of electrical subsystem $c_{subsystem}$ [Euro/kW]	38

To evaluate various wind generator configurations, the used criteria include the generator system cost, the component weight, the generator sizes, the efficiency, the annual energy production (AEP) and the AEP per cost. The following tasks are performed in this report.

1. Developed the design optimization for the investigated wind generator systems.

2. Investigated the optimum gear ratio for the PM generator systems with a single-stage gearbox.

3. Evaluated various wind generator systems with different drive-train concepts for the same generator type

4. Evaluated various wind generator systems with different generators configurations for the same drive-train concepts

5. Numerical evaluation for all the investigated wind generator systems.

1.3.2 Genetic algorithm

The optimization for electrical machines design is a highly nonlinear mix-discrete constrained multivariable problem, the conventional optimization methods, such as the enumerated approach, are not effective in finding the optimum design. As a modern intelligent approach, the genetic algorithm has shown a promising effect and is being widely used for solving the optimization problems for electromagnetic devices [11-13].

1. Description of standard genetic algorithm

The genetic algorithm (GA) belongs to the group of probabilistic searching methods, which have high probability of locating the global optimum in the multidimensional searching space discarding the existing local optimal solutions. The idea of genetic optimization is to imitate evolution in nature. They provide solutions by generating a set of chromosomes referred to as a generation. Each string (chromosome) has its own fitness measure that reflects how well a creature can survive under surrounding environments. The new generation of the strings is created through three major genetic operations – *selection*, *crossover* and *mutation*, which provide a powerful global search mechanism. *Selection* is a process in which individual strings are copied into a mating pool according to their fitness values. *Crossover* is a structured recombination operation. In the classical one-point crossover, a random position in a string is chosen and all characters to the right of this position are swapped. *Mutation* is an occasional random alteration of the value of a string position. A standard GA (SGA) is described by the following steps [11]:

Step 1 Initialize a population of solutions.

Step 2 Evaluate each solution in the population.

Step 3 Create new solutions by mating current solutions: apply three major genetic operations.

Step 4 Delete members of the population to make room for the new solutions.

Step 5 Evaluate the new solutions and insert them into the population.

Step 6 If the available generations have been met, halt and return to the best solution; otherwise go to step 3.

The aim of the algorithm is to find the right genes for a population member thrive in the environment described by the objective functions and the constraints. The feasibility of the design is guaranteed by adding a penalty to the objective function $f(X)$ (e.g. cost) due to constraint violations [11].

$$F(X) = f(X) + \sum_i a_i \left[\max(0, g_i(X))\right]^2 \tag{1-1}$$

where a_i is a scaling parameter and $g_i(X)$ is a constraint function. X is a vector of optimal design variables.

2. Description of improved genetic algorithm

The standard generic algorithms may have some shortcomings such as prematurity, local optimal trap and long time-consuming in solving the optimization of nonlinear complex problems. In this study, an improved genetic algorithm (IGA) is used to optimize the investigated wind generator systems, which was developed and applied to the design optimization of induction machines and power transformers in previous works [12] [13]. Compared to the standard GA, the following key techniques have been revised in the IGA model.

(1) Encoding Scheme

Each string (chromosome) of a SGA is expressed by the binary code of the corresponding objective variables. Owing to frequent encoding and decoding in the process of optimization, it will result in much longer execution time and slower converging speed. To improve the convergent capability, real number code is used to encode and decode for the IGA implementation.

(2) Crossover Operator

To increase the solution space and speed up the convergence of optimization, the IGA uses the stochastic crossover methods incorporating the arithmetic crossover techniques and the uniform crossover schemes. The stochastic crossover strategy is a kind of new crossover operator with parents to bring four offspring. The two offspring are produced by the arithmetical crossover operator, and the others are gained by the uniform crossover operator, which is a standard crossover method of the typical GA.

(3) Mutation Operator

The mutation operator in the SGA processes bit-by-bit the strings undergone the stochastic crossover operator. It is independent of the number of iterations so that it will become more and more inefficient with the development of optimum process. To avoid the aforementioned problems and improve the capability of global search of the standard GA to some extent, a self-adaptive mutation operator is developed as the following

$$x'_k = \begin{cases} x_k + \Delta(t, b_k - x_k) & rd = 0 \\ x_k - \Delta(t, x_k - a_k) & rd = 1 \end{cases} \tag{1-2}$$

Where

$\Delta(t,y) = y(1-r^{t^2})$, *r* is a stochastic number within (0,1), $t = fit(X)/fitm$, $fit(X)$ is the fitness value of the current individual, $fitm$ is the maximal fitness value of current population;

x'_k the *k*th term of the new generation individual X' ;

x_k the *k*th term of the former generation individual X ;

a_k the lower bounds of the variables;

b_k the upper bounds of the variables;

rd the random constant of either “0” or “1”.

(4) Probabilities of crossover and mutation

In order to avoid the local optimization to some extent, the probabilities of crossover and mutation P_c , P_m are dynamically varied with the processing of optimization as

$$\begin{cases} P_c(t) = P_c(t-1) - (P_c^0 - 0.6)/T \\ P_m(t) = P_m(t-1) + (0.1 - P_m^0)/T \end{cases} \tag{1-3}$$

Where t is the current generation; T is the maximum generation， P_c^0 , P_m^0 are the initial value of the crossover and mutation probabilities, respectively.

In addition, the convergent condition of IGA is chosen either the maximal number of generations or the average solution quality.

Table 1-4 shows the main parameters of IGA, which are used to optimize different wind generator systems in this study.

Table 1-4: *The main parameters of IGA*

Parameters	Values
Population size	100
Maximum generation	100
Initial crossover probability	0.90
Final crossover probability	0.6
Initial mutation probability	0.001
Final mutation probability	0.1

Fig. 1-3 depicts the flow chart of IGA procedure.

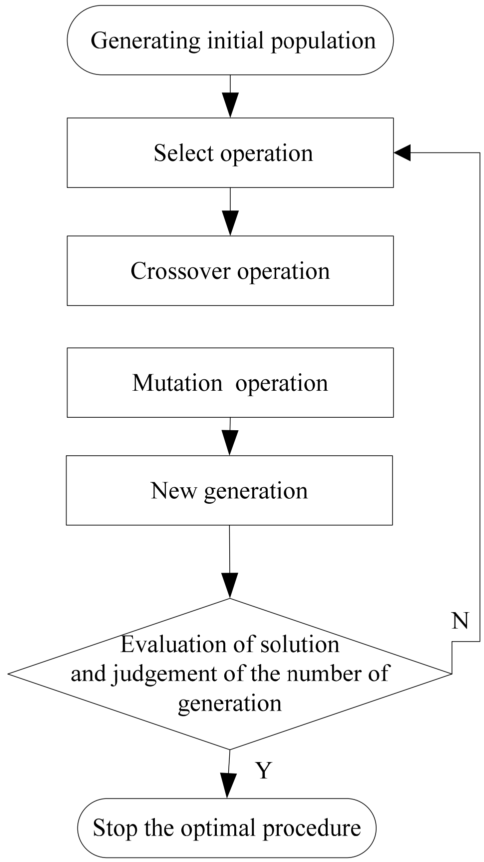


Fig. 1-3: *The flow chart of IGA procedure*

3. Test of IGA

In this study, the design optimization of direct-drive PM generator systems using IGA is demonstrated by comparison with the results from the literature, which can be given in subsection 2.2. In our previous works, the IGA was demonstrated by the optimization of some typical mathematical functions and the design optimization of induction motors and power transformers [12] [13]. For example, the investigated Camel function [12] is given:

$$f(x, y) = (4 - 2.1x + x/3)x + xy + (-4 + 4y)y \tag{1-4}$$

The minimum objective value is -1.031628, and the function exists several optimum solutions. Fig. 1-4 shows the three-dimension representation of Camel function.

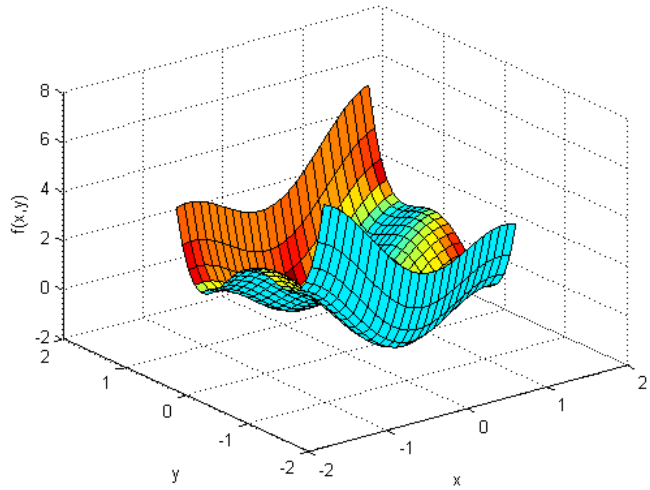


Fig. 1-4: *Three-dimensional representation of Camel function*

The optimization results of the IGA in comparison with those of the SGA are listed in Table 1-5 [12]. Fig. 1-5 depicts the comparison of the objective function values of the optimization proceeding for different optimization methods. It can be seen that the IGA's performance is far better than that of the standard GA.

Table 1-5: *Optimization results of SGA and IGA for Camel function*

Optimization method	x^*	y^*	$f(x^*, y^*)$
SGA	-0.08769	0.72116	-1.029108
IGA	0.09016	-0.71282	-1.031628
	-0.08975	0.71282	-1.031628
	0.08938	-0.71259	-1.031628
	-0.08982	0.71268	-1.031628

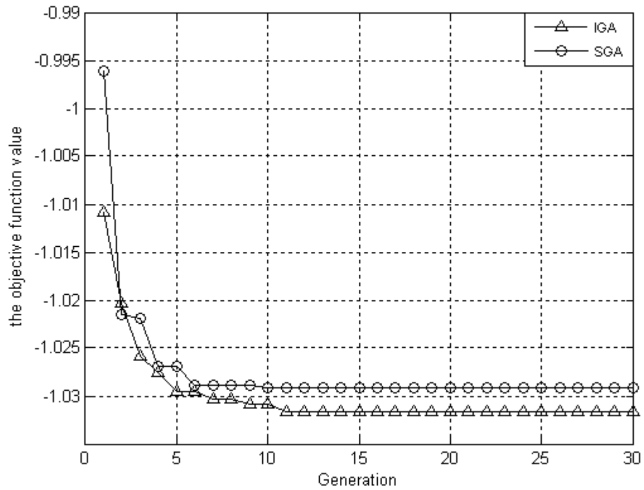


Fig. 1-5: *Time Evolution of the best design*

Table 1-6 depicts the comparison of the optimization results of 3-phase induction motor and the manufacture's data, in which the minimum active material cost was performed for each design. The design models and detailed results of the induction motor were given in the previous work [13].

Table 1-6: *Optimization results of Y-series 3-phase induction motors by IGA [13]*

Types of motor	Rated power [kW]	Cost of manufacturer [Euro]	Optimization of cost [Euro]	Decrease percentage [%]
Y802-2	1.1	7.78	7.22	7.19
Y90S-2	1.5	9.64	8.86	8.09
Y100L2-4	3	18.92	14.3	24.4
Y112M-6	2.2	18,77	17.9	4.63
Y132M-8	3	32.1	28.8	10.28
Y160L-6	11	66.6	57.8	13.21
Y180L-8	11	82.9	74.1	10.61
Y200L-8	15	98.6	89.5	9.23
Y225M-8	22	148.4	135.8	8.49
Y250M-8	30	203.6	169.6	16.70
Y280M-8	45	291.7	237.8	18.48

It could be concluded that the IGA is an effective optimization method, which is suitable to apply to the design optimization of the electrical machines.

1.4 Report organization

This report is organized as follows.

Section 2 presents the optimization models of PM synchronous generator (PMSG) systems, and summarizes the optimization results and evaluation of the direct-drive (PMSG_DD), the single-stage (PMSG_1G) and the three-stage (PMSG_3G) geared drives. It also presents the optimal gear ratio for the design of the PMSG_1G.

Section 3 gives the optimization models of electricity excited synchronous generator (EESG) systems, and summarizes the optimization results and evaluation of the direct-drive (EESG_DD) for different rated power levels.

Section 4 presents the optimization models of doubly fed induction generator (DFIG) systems, and summarizes the optimization results and evaluation of the three-stage (DFIG_3G) and the single-stage (DFIG_1G) geared drives.

Section 5 gives the optimization models of variable speed squirrel cage induction generator (SCIG) systems, and summarizes the optimization results of the three-stage (SCIG_3G) geared drives for different rated power levels.

Section 6 summarizes the results presented in section 2 through 5 to allow a convenient evaluation for each configuration investigated. The numerical evaluations of direct-drive, the single-stage drive, and the three-stage drive wind generator systems are analyzed and discussed, respectively.

2. Design optimization of PM generator systems

The goal of this section is to study the wind turbine design with PM generator systems, which would provide the most cost-effective choice from the direct-drive, the single-stage and three–stage geared drive trains, respectively. The section 2 outline is as follows:

2.1 Description of three drive train concepts: This subsection introduces the advantages and disadvantages of three types of drive train concepts with PMSG system. The largest sizes from manufactures on the current markets are also described for each type.

2.2 Optimization models of PM generator systems: This subsection summaries the optimized variable, the objective function and the mechanical constraints of electromagnetic designs of PM generators. The optimization results of a 500 kW direct-drive PM generator systems are obtained by the IGA, and are demonstrated by the other method from the literature.

2.3 Design optimization and comparison of PMSG_DD systems: This subsection summaries the optimization results of direct-drive PM generator systems for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size and annual energy production (AEP) per cost of PMSG_DD are compared and analyzed.

2.4 Design optimization and comparison of PMSG_1G systems: This subsection presents the optimization results of PMSG_1G systems with the optimum gear ratio of the single-stage gearbox for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The suitable ranges of gear ratios are also investigated.

2.5 Design optimization and comparison of PMSG_3G systems: This subsection presents the optimization results of PM generator systems with a three-stage gearbox for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size and AEP per cost of PMSG_3G are compared and analyzed.

2.6 Evaluation of the PMSG systems with different drive trains: This subsection evaluates the PMSG_DD, PMSG_1G and PMSG_3G systems, and summarizes the results presented in subsections 2.3 through 2.5 to allow a convenient comparison.

2.1 Description of three drive trains

2.1.1 direct-drive train

The direct-drive generator system has high potential for the wind turbines because of its removed gearbox, increased energy yield and reliability in comparison with the geared-drive systems. The grid connection scheme of a PMSG for direct-drive wind turbines is shown in Fig. 2-1.

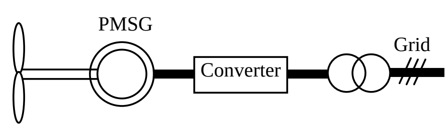


Fig. 2-1: *Scheme of a direct-drive PMSG system (PMSG_DD)*

This configuration is a variable speed wind turbine with a direct-drive PM generator connected to the grid through a full-scale power converter. The most important difference between geared drive wind turbines and direct-drive types is the generator rotor speed. The direct-drive generator rotates at a low speed, because the generator rotor is directly connected on the hub of the turbine rotor. To deliver a certain power, the lower speed makes it necessary to produce a higher torque. A higher torque means a larger size of the generator. Therefore, for direct drive generators, the low speed and high torque operation require multi-pole, which demand a larger diameter for implementation of large number of poles with a reasonable pitch. Moreover, for a larger direct-drive generator, considering on the current loading and gap flux density limitations, a higher torque also requires a larger machine's volume, so that the torque density could not be further significantly increased. To increase the efficiency, to reduce the weight of the active parts, and to keep the end winding losses small, direct-drive generators are usually designed with a large diameter and small pole pitch [3, 4]. In addition, the advantages of direct-drive wind turbines are the simplified drive train, the high overall efficiency, the high reliability and availability by omitting the gearbox.

Compared with the partial-scale power converter, the full-scale power converter can perform reactive power compensation and smooth grid connection over the entire speed range. However, it has a higher cost and a higher power loss in the power electronics, since all the generated power has to pass through the power converter.

In addition, the advantages of PM machines over electrically excited machines can be summarized as follows [3-10]:

• Higher efficiency and energy yield

• No additional power supply for the magnet field excitation

• Improvement in the thermal characteristics of the PM machine due to absence of the field losses

• Higher reliability due to the absence of mechanical components such as slip rings

• Lighter so that higher power to weight ratio

However, PM machines have some disadvantages which can be summarized as follows:

• High cost of PM material

• Difficulties to handle in manufacture

• Demagnetization of PM at high temperature

In recent years, the use of permanent magnets (PMs) is more attractive than before, because the performance of PMs is improving and the cost of PM is decreasing. The trends make PM machines with a full-scale power converter more attractive for direct-drive wind turbines.

Currently, Zephyros (currently Harakosan) and Mitsubishi are using this concept in 2 MW wind turbines on the market. Fig. 2-2 shows 2 MW direct-drive PM generator system of Zephyros (currently Harakosan).

Fig. 2-2: *Zephyros Z72-2MW (PMSG_DD) [14]*

2.1.2 Single-stage geared drive train

Due to the low speed operation, direct drive PM wind turbine concepts have disadvantages as the large diameter, heavy weight, and expensive cost of generators. With the increase of rated power levels and the decrease of wind turbine rotor speeds, these direct-drive systems are becoming larger and even more expensive, more difficulties of transport and assembly. Therefore, an interesting alternative may be a mixed solution with a single-stage planetary gearbox and a medium-speed PM generator, which was first introduced by Multibrid of Germany [15]. Fig. 2-3 shows the grid connection scheme of this concept

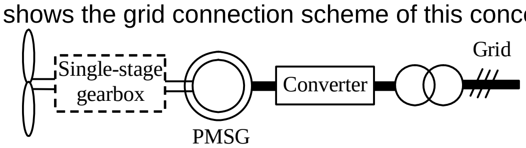


Fig. 2-3: *Scheme of a PMSG system with a single-stage geared drive (PMSG_1G)*

In this wind turbine concept, the generator, gearbox, main shaft, and shaft bearing are all integrated within a common housing. The common generator-gearbox housing is supported by a tubular bedplate structure. The tower-top assemblies are enclosed with a non-structural fibreglass nacelle cover [16, 17]. This concept has gained the attention because it has the advantages as lower generator costs than the direct-drive concept, and lower gearbox costs, higher availability and operating reliability than the multiple-stage geared drive concept. Currently, Wind turbine manufacturers, such as Multibrid (MB5000-116, See Fig. 2-4) [15] and WinWinD (WWD-3, See Fig. 2-5) [18] are developing this concept on the current market. The plan is to employ Multibrid-type plants for the first time offshore in Borkum-West in 2006-2007 [17].

Fig. 2-4: *Multibrid M5000-116, 5MW (PMSG_1G)*

Fig. 2-5: *WinWind WWD3, 3MW (PMSG_1G)*

2.1.3 Three-stage geared drive train

A PMSG system with a multiple-gearbox is used in order to further reduce the PM generator's volume and improve the generator efficiency in variable speed wind turbine concepts with a full-scale power converter. Fig. 2-6 shows the grid connection scheme of this concept.

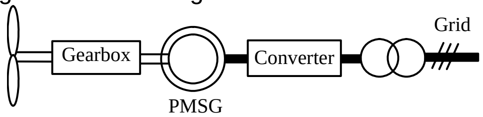


Fig. 2-6: *Scheme of a PMSG system with a three-stage geared drive (PMSG_3G)*

Compared to the multi-stage geared drive DFIG system, this wind generator configuration has the following advantages:

• The generator has a better efficiency.

• The generator can be brushless.

• The grid-fault ride through capability is less complex.

And the following disadvantages:

• Larger, more expensive converter (100% of rated power instead of 30%).

•The losses in the converter are higher because all power is processed by the power electronic converter.

On the market, this configuration has been used in GE multi-megawatt series (See Fig. 2-7) [19], and Spanish manufacturer Made. The 2.5 MW Clipper Liberty turbine type, which features four 660 kW PMSGs, has also used this concept.

Fig. 2-7: *GE 2.5MW (PMSG_3G)*

2.2 Optimization models of PM generator systems

The analytical design models of PM generator have been presented in subsection 5.2 of report 1. In this subsection, the optimization models of PM generator systems are introduced, and the design results of a 500-kW direct-drive PM generator system are obtained to demonstrate the electromagnetic designs and the optimization models.

2.2.1 Optimization models

1. Objective function

In order to obtain the most cost-effective PM generator system, the proposed criterion includes the generator system cost

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} + C_{gear} \tag{2-1}$$

where

$C_{g\_act} = c_{cu} G_{cu} + c_{Fe} G_{Fe} + c_m G_m$ generator active material cost;

c_{cu}, c_{Fe}, c_m are the unit costs of the copper, the active iron and the PMs, respectively;

G_{cu}, G_{Fe}, G_m are the weight of the copper, the active iron and the PMs, respectively.

C_{g_str} generator structural cost, which is approximated as $C_{g\_str} = c_{str} \frac{1}{2}\left[(\frac{D_1}{2})^3 + (L_{tot})^3 \right]$, c_{str} is the unit cost of a reference structure of 2m diameter and 1m length [4].

C_{con} cost of power electronic converter.

$C_{subsystem}$ other electrical subsystem cost, which includes transformer, cable, switchgear and so on.

C_{gear} single-stage or three-stage gearbox cost (if present).

For this criterion, the different specific component costs are given in Table 1-3, respectively.

2. Optimized variables

In order to optimize the machines to the criterion (2-1), six variables are chosen to vary within a certain range, including the air gap radius (r_s), the stator length (L), the slot height (h_s), the pole pitch (τ_p), the peak air gap flux density ($\hat{B}_{g0}$) and the peak stator yoke flux density ($\hat{B}_{ys}$). The ranges of r_s, L, τ_p, h_s varies with different rated powers, whereas the ranges of $\hat{B}_{g0}$, $\hat{B}_{ys}$ are fixed to 0.7-1T and 0.7-1.2T in the design optimization of different rated powers.

3. Assumptions and constraints

The following assumptions are used in the optimization program:

•The number of slots per pole per phase is $q = 1$, in order to allow for a small pole pitch without getting a low slot fill factor because of narrow slots.

•A two-layer winding with two conductors per slot ($N_{slot} = 2$) is used to make the end windings simple due to an integer slot winding.

•The stator slots are open and a non-magnetic wedge thickness is $h_w = 5$ mm.

•The slot filling factor is set to a constant value, i.e. it is 0.65 for the stator outer diameters larger than 2m; below 2m, it is assumed to be 0.4.

•The slot width is assumed to be 45% of the slot pitch and the stator slots are skewed by one slot pitch, so that the torque ripple can be reduced [4] [19] [20].

•For mechanical reasons, the ratio of slot depth to slot width is limited over the range of 4-10, which prevents excessive tooth mechanical vibrations from occurring.

•The air gap is equal to 0.001 of the air gap diameter; however a mechanical air gap of at least 5mm is mechanically required for large direct-drive PM generators.

•The magnet width b_m is kept at 70% of the pole pitch, but the minimum value is limited to be larger 3 times the air gap thickness to reduce the tangential fringing flux of the PMs in the air gap [20].

• In order to use the control mode of operation for the lowest power rating requirements on both generator and rectifier, so that it can utilize the PMSG and converter best, the values of X_s is limited to 0.5-1.5 pu [3]

•To avoid demagnetization of the magnets, the peak flux density generated by the stator winding $\hat{B}_s$ is limited to be smaller than $\hat{B}_{g0}$. During normal operation, $\hat{B}_s$ depends on the peak value of the stator magnet-motive force (mmf) $\hat{V}_s$ and the effective air-gap length g_{eff}, which is given as $\hat{B}_s = \mu_0 \dfrac{\hat{V}_s}{g_{eff}}$. In addition, since the PM cover a pole arc of 126 degrees ($b_m = 0.7\tau_p$), the ratio of leakage inductance to magnetizing inductance is also limited to be larger than 1.27 to avoid the risk of demagnetization at a short circuit at the generator terminals [4].

•The maximum flux density in the stator and rotor yoke is set to 1.2T, in order to reduce the drop in mmf in those parts [8]. This also reduces iron losses in the stator yoke. The iron losses in the rotor and the rotor saliency are neglected, respectively;

•The current density in the stator windings is limited to 3-6 A/mm^2, and the current loading is limited to 40-60 kA/m to prevent excessive cooling requirements [20].

4. Optimization methods

In this study, an improved genetic algorithm (IGA) is used to optimize the various types of drive train with PMSG, which has been described in subsection 1.2. Fig. 2-8 depicts the flow chart of the main computation procedure for the optimization of PM generator systems.

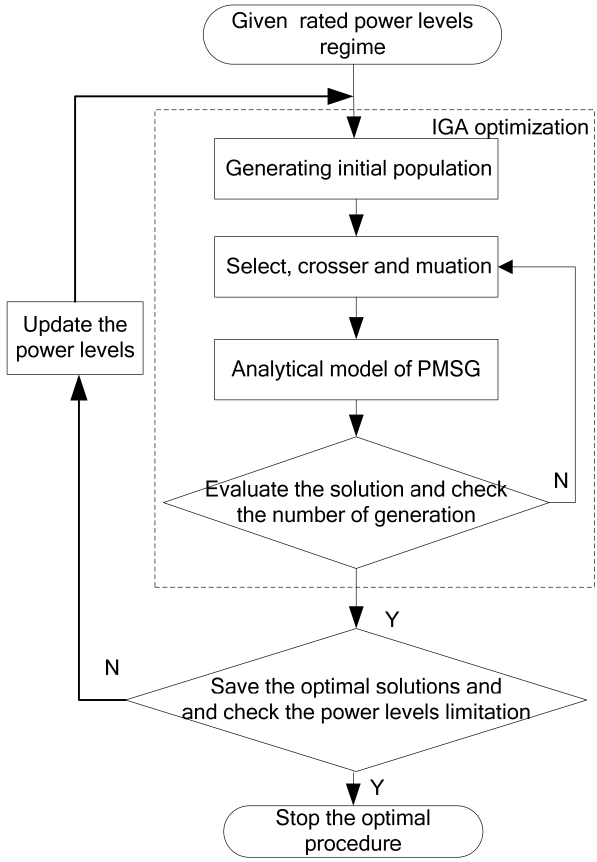


Fig. 2-8: *The flow chart of the optimization procedure of PMSG for each rated power*

Firstly, at a given rated power and a gear box (if present), the initial population is randomly generated by the six variables within a specific range. Next, according to the IGA models and the analytical models of the radial-flux PM generator, the optimization is implemented for the sake of obtaining the minimal generator system cost. The constraints including the mentioned assumptions can be fulfilled for the design optimization. Once the best design is obtained, the program will update the next PM generator system and repeat the optimization. After the optimal designs in the given range of the investigated PM generator systems are finished, the optimization program stops. In addition, when the gear ratio is taken as an optimized variable, the optimal gear ratio of the most cost-effective PMSG_1G system can be also obtained by using this optimization program.

2.2.2 Test of design optimization

In order to demonstrate the electromagnetic designs and the optimization models, a 500-kW direct-drive PM generator system with a rated speed 32 rpm has been chosen. Table 2-2 shows the detailed comparison of the IGA and the optimization by A. Grauers [4].

Table 2-2: *Comparison of the optimized 500-kW direct-drive PM generator system*

Design specification	IGA	Optimization in [4]
Air gap radius r_s [m]	1.13	1.08

Stator length L [m]	0.54	0.55
Stator slot height h_s [mm]	60	64
Pole pitch T_p [mm]	61.1	68.3
Peak air gap flux density B_{g0} [T]	0.78	0.77
Peak stator yoke flux density B_{ysm} [T]	1.13	1.2
Main dimensions		
Air gap [mm]	2.26	2.15
Stator slot width b_s [mm]	9.2	11.7
Stator tooth width b_d [mm]	11.2	11.1
Stator yoke height h_{ys} [mm]	14.2	15.9
Rotor yoke height h_{yr} [mm]	14.2	15.4
Magnet height h_m [mm]	5.8	6.3
Magnet width b_m [mm]	42.4	47.8
Performance parameters and material weight		
Number of pole pairs N_p	58	50
Generator output frequency [Hz]	30.9	26.5
Current density [A/mm^2]	4.02	3.6
Stator yoke losses [W]	784	760
Stator teeth losses [W]	2510	1950
Full load efficiency [%]	94.15	94.2
Magnet weight [kg]	121	124
Copper weight [kg]	630	779
Core weight [kg]	1860	1786
Total active material weight [kg]	2611	2690

Because the used specific costs are different, the costs of the components have not been shown in Table 2-2. However, from the optimal results presented in Table 2-2, it can be seen that the good agreement exists with respect to the generator dimensions and performances by the IGA and that by the numerical optimization method [4]. The lower total active material weight can be obtained by using the IGA.

In addition, in order to show the optimization capability of the IGA, Fig. 2-9 depicts the evaluation of the best design of the optimization proceeding. As it can be seen, after 40 generations, the results improve very little. A total number of generations 100 is sufficient.

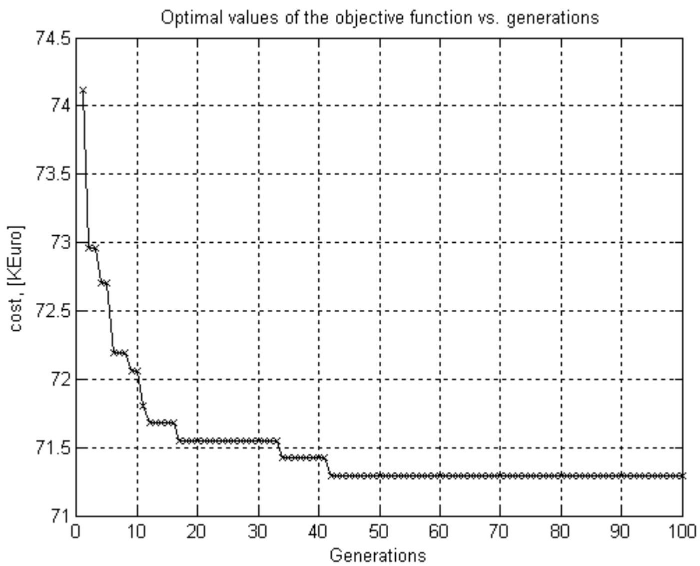


Fig. 2-9: *Time Evolution of the best design for the 500kW optimization*

From the above comparison, the optimization models and the IGA method have demonstrated the effectiveness, and will be further applied to the optimization of the PM generator systems with different drive trains.

2.3 Design optimization and comparison of PMSG_DD systems

Direct drive wind generator system costs are mainly dependent on the chosen generator diameters. Basically, larger generator diameters decrease the necessary generator length and active magnetic material costs, but increase the generator structural costs, technical difficulties of transport and assembly. So it is necessary to present a numerical evaluation of the most cost-effective direct-drive PM wind generator systems by the optimization design.

In order to investigate the performances of the direct-drive PM wind generator systems over a range of power ratings, the mentioned optimization models are used to optimize the PMSG_DD systems for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size, efficiency and the AEP per cost are compared graphically as the following, respectively.

1. *Generator system cost*

Fig.2-10 depicts the generator system cost function for the optimization designs. In order to see the component costs at different rated powers, the costs of the generator active material, the generator structure and the power electronic converter are also shown in Fig. 2-10.

The results show that the generator structural cost and the active material cost are the main components of the generator system cost. The generator active material cost increase almost linearly with the rated power, however, the cost of the generator structure may rise more than linearly. Since the generator structural cost may be larger than the generator active cost, for example for the rated power of 10-MW, the structural cost is almost 2 times the active material cost, the generator system cost increase more than linearly with the rated power for larger than 3MW power ratings.

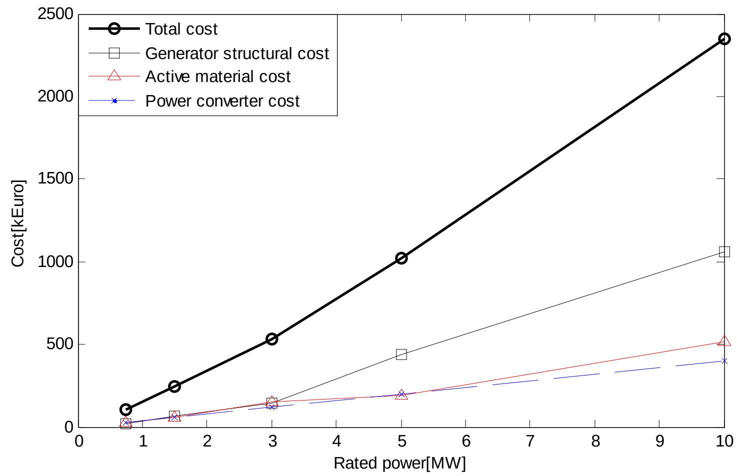


Fig.2-10： *The PMSG_DD system cost as a function of rated power*

2. Generator system weight

The weight of the generator is usually not a problem for the wind energy conversion during operation. Forces on the wind turbine tower, for instance, are determined almost exclusively by the forces from the wind turbine, not by the generator weight. Nevertheless, the weight could be also important for the erection of the wind energy conversion [4]. A heavy generator demands a larger crane or that the machinery be lifted in several parts. Since the mechanical part of the generator has not been designed, only the active weight is calculated in this study. The weight of the generator structure may be expected to be much higher than the active weight [4]. Fig.2-11 depicts the active material weight of the direct-drive PM generator as a function of rated power. It can be seen that the iron weight is larger than the copper weight and the PM weight, and the weights of the active materials increases slightly more than linearly.

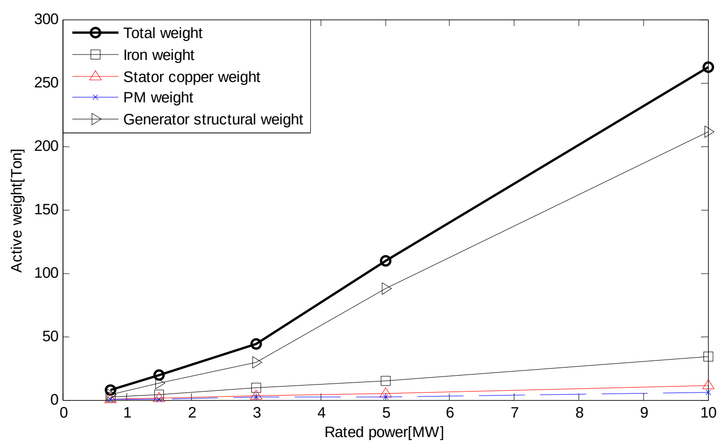


Fig.2-11：*The weight of the PMSG_DD as a function of the rated power*

3. Generator size

The size of the direct-drive wind generator is important. Generators will be more difficult to manufacture as their sizes increasing, but an even more important problem might be the transportation to the site. The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 2-12. It can be seen that the outer diameter and the length increases with increasing rated power, but the increase of the outer diameter is rather larger. For example, an optimized 0.75-

MW generator has an outer diameter of 2.7m and a 10-MW generator 10.2m. The corresponding stator lengths are 0.8m for the 0.75-MW generator and 2.0m for the 10-MW generator. In addition, when the rated power is larger than 3MW, the outer diameter may exceed 5.0m, so that it could lead to have more difficulties of transport and assembly.

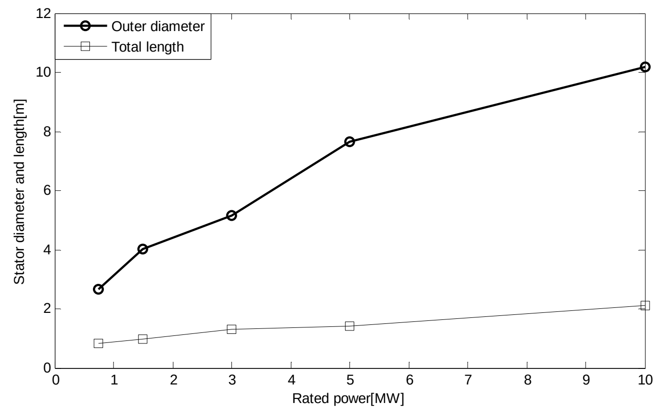


Fig.2-12：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the loss of the power electronic converter at rated load for the optimized PMSG_DD systems are shown in Fig. 2-13. The efficiency of the direct-drive PM generators increases with the rated power, as it also does for conventional generators. An important reason for the increase in efficiency is that the rotor surface velocity increases; a higher rotor surface velocity means that a higher active power can be produced per square meter of air gap surface with a given force density [4]. The generator efficiency increases from 92.8 % for a 0.75-MW generator to 96.7 % for a 10-MW generator, and the rotor surface velocity increases from 3.83 to 5.24 m/s. The system efficiency at rated load is about 3 percent lower than the generator efficiency due to the full scale power electronic losses.

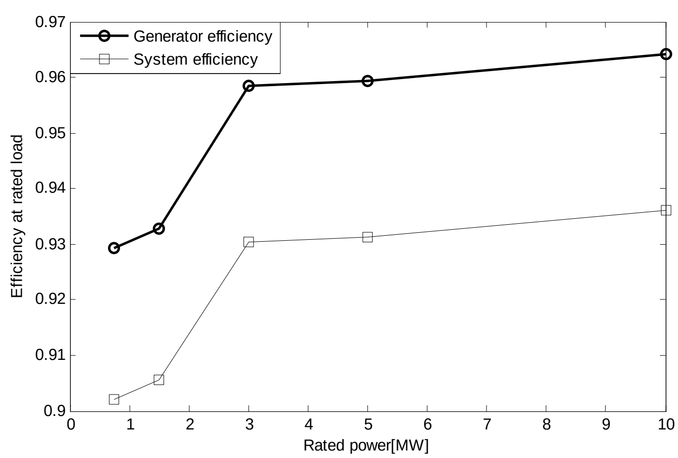


Fig.2-13：*The efficiency at full load as a function of rated power*

5. AEP per cost

In order to calculate the annual energy production (AEP) of wind generator systems, the wind site with the annual average wind speed of 7m/s at 10m height is investigated, and the corresponding mean wind speeds at the hub height for each design are given in Table 1-1. Fig. 2-14 depicts the AEP per cost as a function of the rated power. The AEP per cost is an effective index to evaluate the individual wind energy conversion, in which only the generator system cost is considered (see Fig. 2-10). The results shown the optimized PMSG_DD systems have a slight decreasing in AEP per cost as the power ratings increase. This may be a reason that the cost of the direct-drive generator system could rise more rapidly than the energy production.

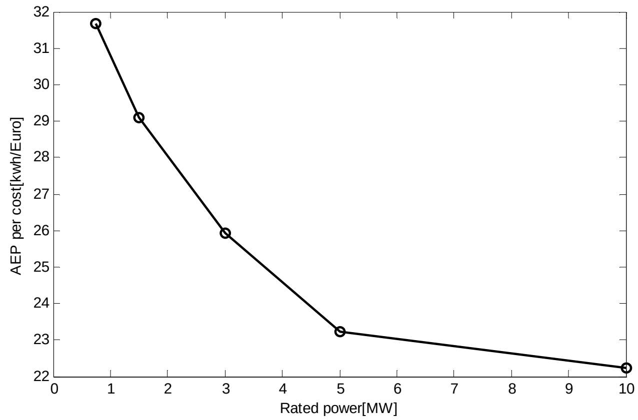


Fig.2-13：*The AEP per cost as a function of rated power*

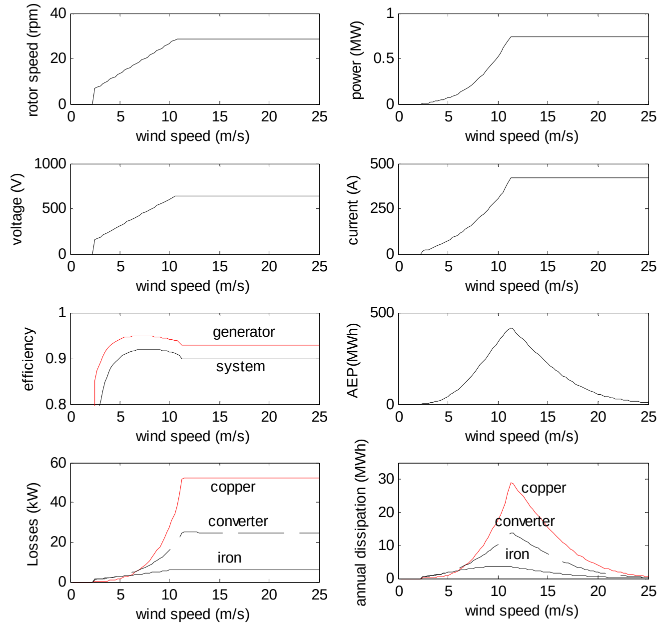
As a design reference of direct-drive PM generators, Table 2-3 summarizes the system important dimensions and performances resulting from each optimal design.

Table 2-3: *Main Performances of the optimized PMSG_DD systems*

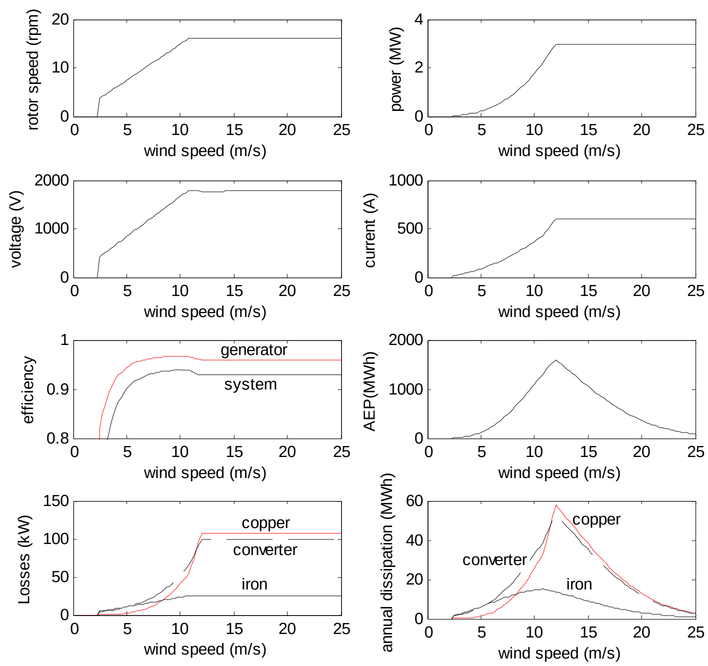
Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter *D* [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.3	11.3	12	12	11.7
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
PM Generator system dimensions and electrical performances					
Air gap diameter D_{i1} [m]	2.56	3.9	5.0	7.5	10.0
Stator length *L* [m]	0.73	0.88	1.2	1.25	1.94
Pole pitch *Tp* [mm]	42.2	50.5	60.0	80.1	80.3
Stator slot height h_s [mm]	44.0	42.1	64.4	58.9	69.0
Stator slot width b_s [mm]	6.3	7.6	9.0	12.0	12.1
Stator tooth width b_d [mm]	7.8	9.3	11.0	14.7	14.8
Stator yoke height h_{ys} [mm]	10.2	12.0	15.9	16.5	17.6
Rotor yoke height h_{yr} [mm]	10.2	12.0	15.9	16.5	17.6
Magnet height h_m [mm]	7.1	12.4	18.5	12.7	19.2
Magnet width b_m [mm]	29.5	35.3	42.0	56.1	56.2
Peak air gap flux density B_{g0} [T]	0.83	0.81	0.91	0.71	0.75
Peak stator yoke flux density B_{ysm} [T]	1.198	1.194	1.198	1.197	1.196

Number of pole pairs N_p	95	121	131	147	196
Generator output frequency [Hz]	45.3	41.3	34.9	36.3	32.7
Generator output phase voltage [V]	639	1050	1770	2228	4431
Generator output phase current [A]	423	506	599	801	801
Stator resistance [pu]	0.065	0.063	0.034	0.036	0.030
Synchronous inductance [pu]	0.631	0.529	0.509	0.573	0.540
Current density [A/mm^2]	5.26	5.52	3.45	3.80	3.21
Full load generator efficiency [%]	92.9	93.3	95.85	95.94	96.4
Full load system efficiency [%]	90.2	90.6	93.0	93.1	93.6
Generator material weight [Ton]					
Iron	2.04	3.95	9.79	14.85	34.31
Copper	0.67	1.16	3.21	4.65	10.96
PM	0.22	0.71	1.85	1.98	6.19
Total weight	**2.93**	**5.82**	**14.85**	**21.48**	**51.47**
Generator construction weight[Ton]					
Total weight	**4.37**	**13.50**	**29.22**	**88.15**	**211.22**
Component cost [kEuro]					
Generator active material	25.1	57.7	151.4	193.7	515.1
Generator construction	21.9	67.5	146.1	440.7	1056
Power electronic converter	30	60	120	200	400
Electrical subsystem	28.4	56.7	113	189	378
Generator system cost	**105**	**242**	**531**	**1024**	**2350**
Cost per kilowatt [Euro/kW]	**141**	**161**	**177**	**205**	**235**
Annual energy					
Copper loss [MWh]	202	417	428	861	1633
Iron loss [MWh]	39	64	164	160	377
Converter loss [MWh]	110	233	452	810	1780
Total loss [MWh]	351	714	1044	1830	3790
AEP [GWh]	**3.34**	**7.04**	**13.76**	**23.77**	**52.26**
AEP per cost[kWh/Euro]	**31.67**	**29.09**	**25.92**	**23.22**	**22.24**

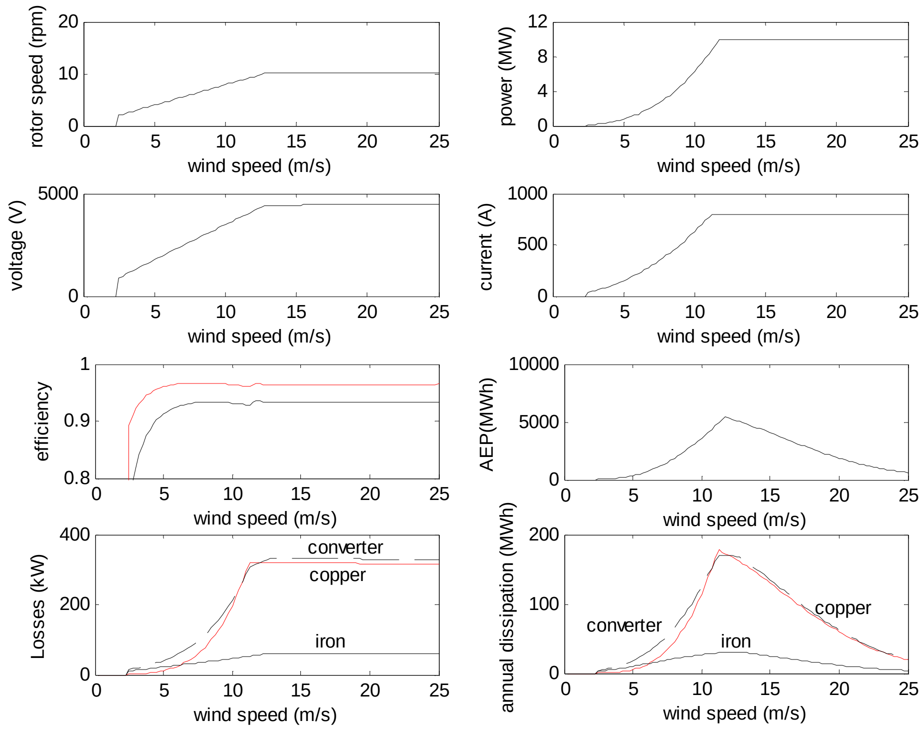
In order to further show the operational performances of direct-drive PM wind generator systems, as for examples of small, middle and large PMSG_DD systems, Fig. 2-15 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW PMSG_DD systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW PMSG_DD



(b) 3.0-MW PMSG_DD



(c) 10.0-MW PMSG_DD

Fig.2-15：*The characteristics of the PMSG_DD system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and annual energy dissipation are also shown in Fig. 2-15, according to the annual mean wind speed 7.0m/s at 10m height. It can be seen that the losses dissipation is different for different rated power PM generator systems. For example, for a relative small PM generator system (0.75-MW), the largest part of the losses is losses in the stator copper, which is almost over 50% of the annual dissipation in the generator system. However, the largest part of the losses may be losses in the converter as the turbine size increases, for example the converter loss is over 50% of the annual dissipation in the generator system at the rated power of 10-MW. In addition, the iron losses in the generator at the rated wind speed are small, but they are larger than the copper losses at wind speeds of 6-8m/s.

By comparison of the optimization results of direct-drive PM wind generator systems at different rated power levels, it can be seen that the stator outer diameter rapidly increases as turbines size increases. When the power rating of the direct-drive PM wind generator system is larger than 3MW, the outer diameter may exceed 5m, the generator structure cost may increase quicker than the generator active material cost, and the AEP per cost also rapidly decrease due to the increase of the specific cost per kilowatt. From these aspects, the upper power limit for the studied direct-drive PM wind generator systems seems to be less than 3MW. If the larger power ratings need to design, special methods for transport may need for further consideration, due to the increases of the stator outer diameter.

2.4 Design optimization and comparison of PMSG_1G systems

The cost of PM wind generator system with a single-stage gearbox drive is mainly dependent on the choice of gearbox ratios and generator diameters. Higher gearbox ratios increase the generator speed, decreasing the size and cost of the generator. However, higher gearbox ratios increase the gearbox size and cost. In addition, larger generator diameters decrease the necessary generator length and active material cost, but drive up the structural costs for the larger housing. In this case, the question arises whether the PMSG_1G system has the suitable ranges of gearbox ratios to have more cost-effective performances. Therefore, the system optimization is necessary to determine the gearbox ratios and generator diameters for this wind turbine concept.

In this section, firstly, the weight and cost of the single-stage planetary gearbox are presented at different power levels and different gear ratios. Next, the design optimization and comparison of the PMSG_1G systems with a given gear ratio in a certain range are investigated. Finally, the optimum gear ratio of the most cost-effective PMSG_1G system is obtained for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW, respectively, when the gear ratio is taken as an optimized variable.

2.4.1 Weight and cost of the single-stage planetary gearbox

As the gear ratio increases, increasing the generator speed reduces the size and the cost of the generator; however, higher gearbox ratios increase the gearbox mass and cost. Therefore, weight and cost of the gearbox at different power levels and different gear ratios have to be considered.

Due to its compact and lightweight, a single-stage planetary configuration is used to investigate the most-effective PM generator system with the single-stage gearbox drive train. The weight and cost models of the single gearbox stage have been presented in section 3 of the report 1.

Because large planet gears are required to facilitate large bearings with adequate lifetime, a ratio range of 3:1 to 15:1 is possible for the single-stage planetary gearbox [21]. According to the presented models, the gearbox weight and cost can be estimated for a given wind turbine. Figs. 2-16 and 2-17 depict the weight and cost functions of the single-stage planetary gearbox with different gear ratios. In order to compare the model calculations, the weight and the cost estimate of the 1.5MW single-stage planetary gearbox from Milwaukee Gear [5] are also shown.

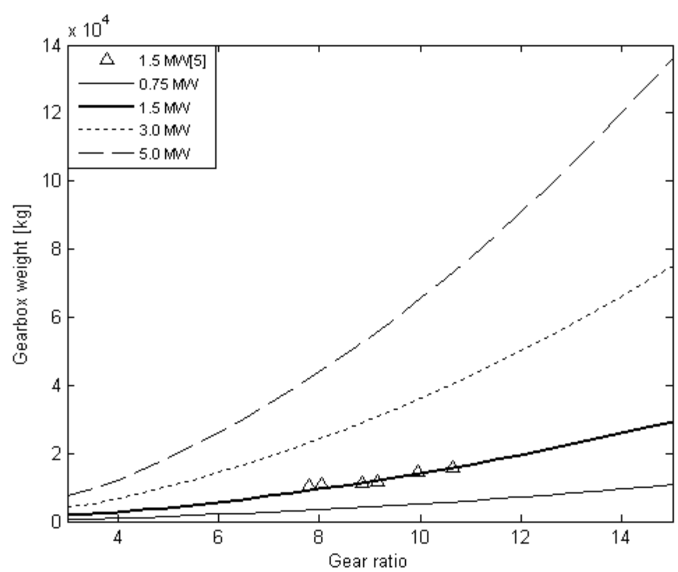


Fig.2-16：*The weight function of the single-stage gearbox*

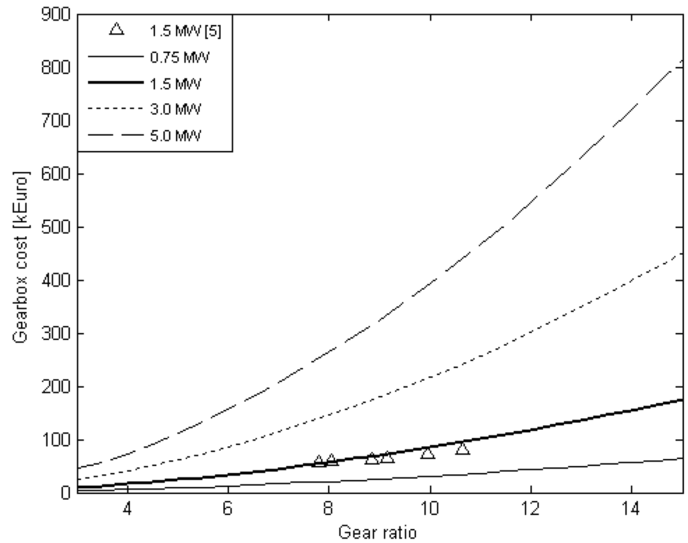


Fig.2-17：*The weight function of the single-stage gearbox*

The weight and cost of the single-stage gearbox increase with the increase of gear ratio and power ratings. From the comparison of 1.5-MW gearbox, it can be seen that the results of the model calculations are close to manufactures data.

2.4.2 Optimization results for a given gear ratio

In order to investigate the performances of the PMSG_1G systems over a range of gear ratios at different rated power levels, the PM generator system is optimized for each design with a given gear ratio. In this case, the gear ratio range from 3:1 up to 15:1 is investigated.

Fig. 2-18 shows a three-dimensional representation in terms of the generator system cost (criterion) for the optimized PM generator system with a given gear. Fig. 2-19 depicts the cost curves for different gear ratio at the optimized 1.5-MW output rating, along with the different components cost. Compared to the direct-drive concept, the optimization results show the PMSG_1G system cost firstly decreases as the gear ratio increases, because the cost reduction of the generator is lager than the cost increase of the gearbox. Then the higher gearbox ratios rapidly increase the gearbox cost, so that the total cost may increase even though the costs of the generator active material and the generator structure reduce.

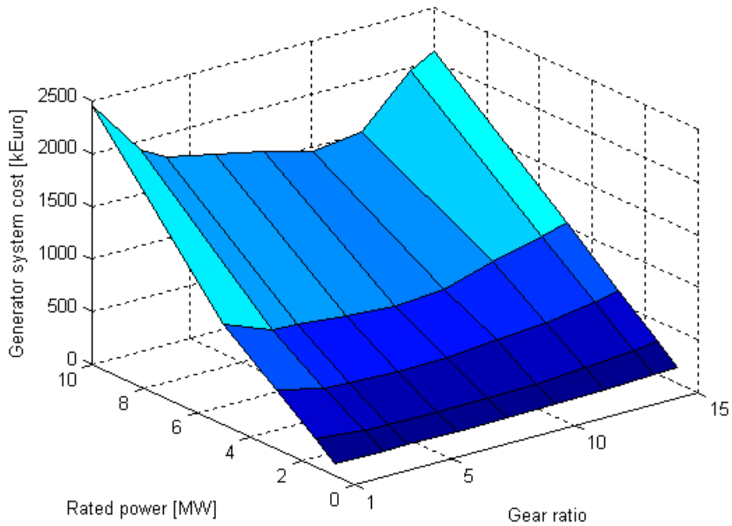


Fig.2-18：*Three-dimensional representation of the optimized system cost*

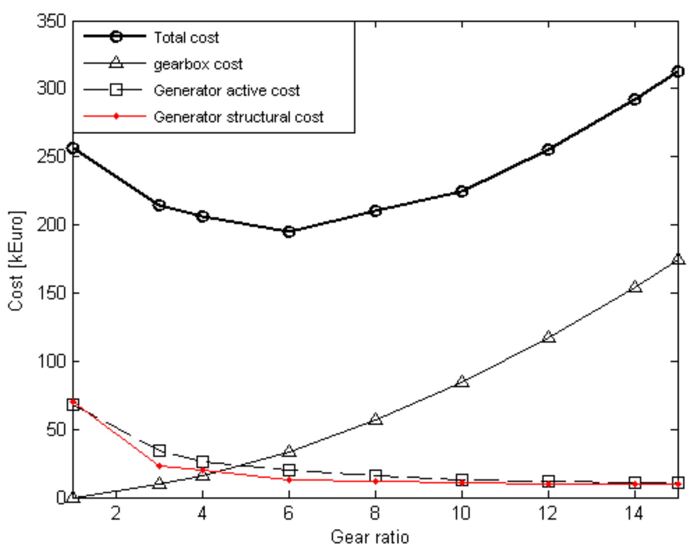


Fig.2-19：*Component costs for different gear ratio at the 1.5-MW output rating*

Fig.2-20 shows a three-dimensional representation in terms of the AEP per cost for the optimized generator system with a given gear ratio.

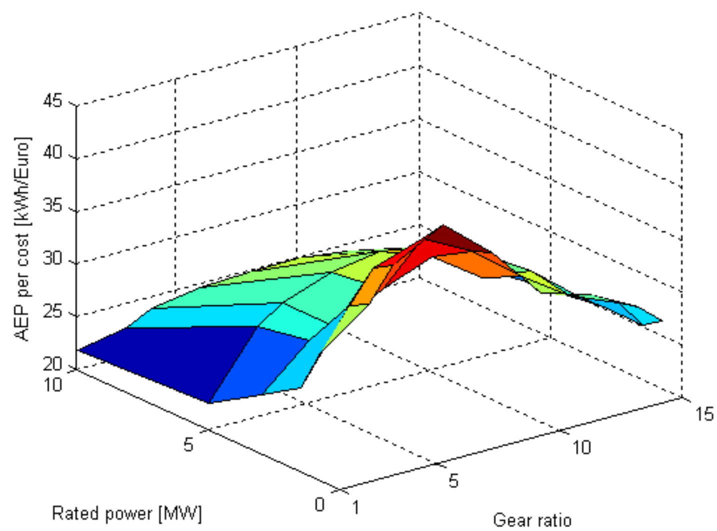


Fig.2-20：*Three-dimensional representation of AEP per cost*

It can be concluded that the PMSG_1G configuration has higher AEP per cost than the direct drive (In this case, the gear ratio '"1" represents the direct-drive concept). From the viewpoints of the generator system cost and the AEP per cost, there exists an optimum gear ratio for the most cost-effective PMSG_1G system at a given rated power.

2.4.3 Results and comparison with the optimum gear ratio

In order to obtain the optimum gear ratio for the PMSG_1G systems, the gearbox ratio is further taken as an optimized variable in the IGA program, so that the most cost-effective PMSG_1G system can be obtained for a given rated power. The cost, weight, size, efficiency and AEP per cost of the optimum PMSG_1G systems are compared graphically as the following, respectively. The results at different rated power corresponds to their optimum gear ratio are shown Table 2-4, respectively.

1. Generator system cost

Fig.2-21 depicts the generator system cost function for each optimization design with the optimum gear ratio. In order to see the component cost at different rated powers, the cost of the generator active materials, the generator structure, the single-stage gearbox and the power electronic converter are also shown in Fig. 2-21.

The results show that the single-stage gearbox cost and the power electronic converter cost are the main components of the generator system cost with the turbine sizes increase. The single-stage gearbox cost increase almost linearly with the rated power, however, it may rise more rapidly when the rated power exceeds 5MW, so that the generator system cost increase rapidly from 5-MW to 10-MW.

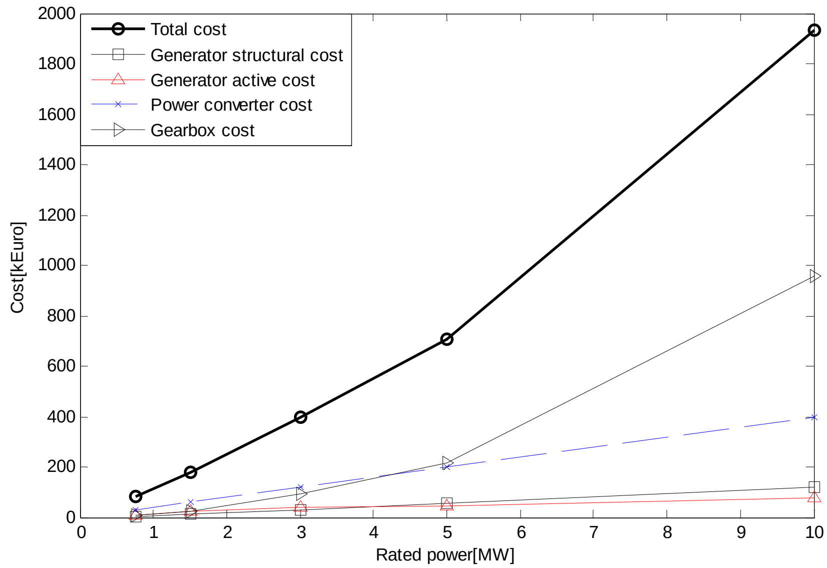


Fig.2-21： *The PMSG_1G system cost as a function of rated power*

2. Generator system weight

In this case, the generator system weight including the active material part and the single-stage gearbox are shown in Fig.2-22. It can be seen that the single-stage gearbox weight is a large part of the generator system weight.

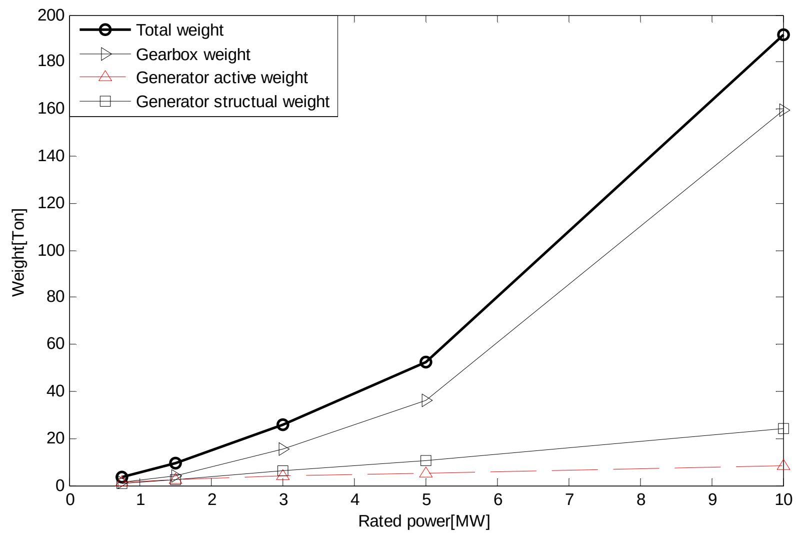


Fig.2-22：*The weight of the PMSG_1G as a function of the rated power*

3. Generator size

The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 2-23. It can be seen that the outer diameter and the length increases with increasing rated power, but the outer diameter may be less than 5.0m when the rated power increases towards 10 MW. Therefore, by using the single-stage gearbox, the large wind turbine system could avoid the technical difficulties of transport and assembly resulting from the large outer diameter.

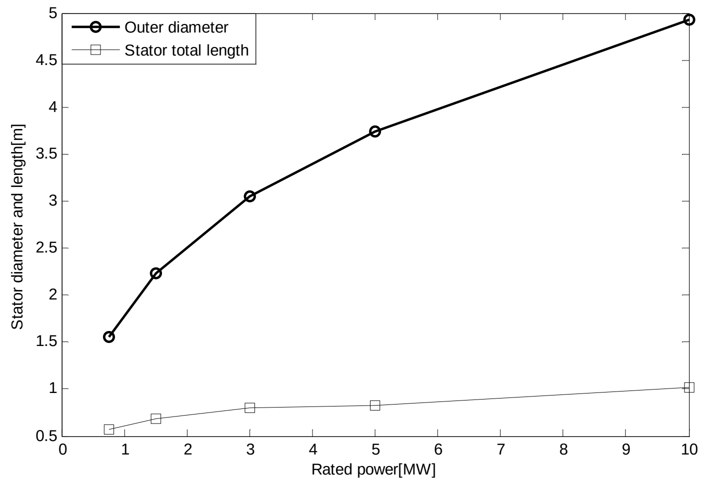


Fig.2-23：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the loss of the power electronic converter and the single-stage gearbox at rated load are shown in Figure 2-24. Both the generator efficiency and the system efficiency increase with the increasing of the rated power. The system efficiency at rated load is about 4 percent lower than the generator efficiency due to the power electronic losses and the single-stage gearbox losses.

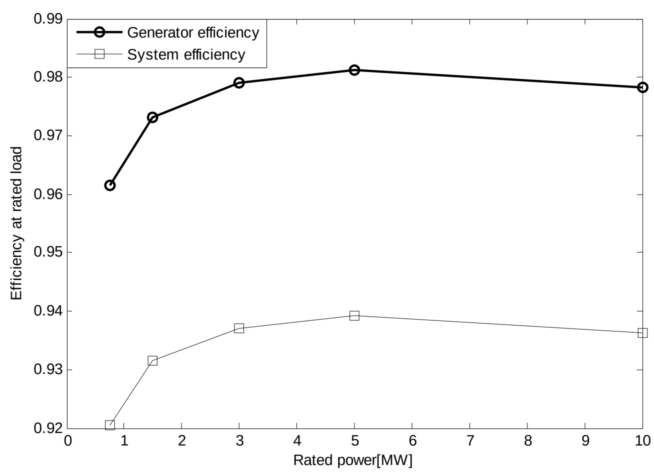


Fig.2-24：*The efficiency at full load as a function of rated power*

5. AEP per cost

Fig. 2-25 depicts the AEP per cost as a function of the rated power, in which the cost is considered by the generator system cost (see Fig. 2-21).

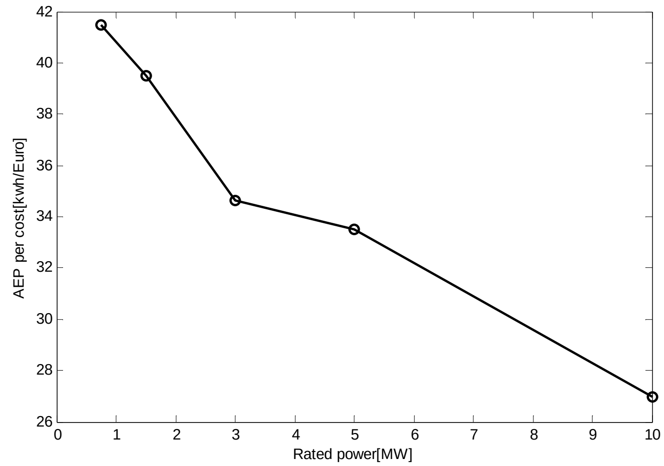


Fig.2-25：*The AEP per cost as a function of rated power*

The results show the optimized PMSG_1G systems have a slight decreasing in AEP per cost as the power ratings increase, but the decrease is rather large when the rated power exceeds 5MW. This may be a reason that the cost of the single-stage gearbox could rise more rapidly than the energy production.

As a design reference of PM wind generators with a single-stage planetary gearbox, Table 2-4 summarizes the system important dimensions and performances resulting from each power level.

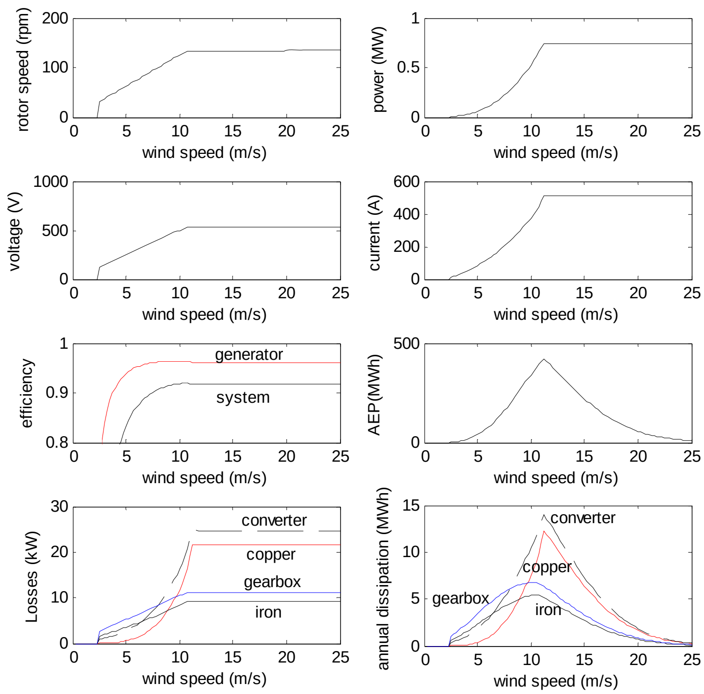
Table 2-4: *Main Performances of the optimized PMSG_1G systems*

Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter *D* [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.2	11.2	11.9	12.0	11.7
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Optimal gear ratio	4.68	5.17	6.27	7.25	9.02
PM Generator system dimensions and electrical performances					
Generator rated rotor speed [rpm]	134	106	100	107	90
Air gap diameter D_{i1} [m]	1.4	2.1	2.9	3.6	4.8
Stator length *L* [m]	0.46	0.57	0.65	0.68	0.92
Pole pitch *Tp* [mm]	50.6	60	71	70.7	50.3
Stator slot height h_s [mm]	62.3	51.7	58.4	56.5	53.9
Stator slot width b_s [mm]	7.7	9.0	10.7	10.6	7.5
Stator tooth width b_d [mm]	9.4	11	13	12.9	9.2

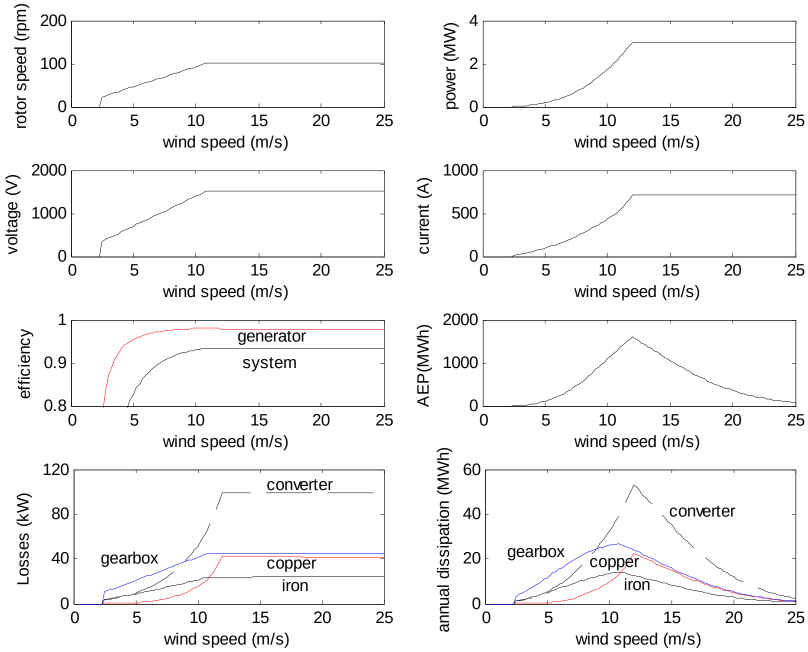
Stator yoke height h_{ys} [mm]	13.4	14.2	16.1	15.6	11.1
Rotor yoke height h_{yr} [mm]	13.4	14.2	16.1	15.6	11.1
Magnet height h_m [mm]	6.5	12.4	11.3	10.3	10
Magnet width b_m [mm]	35.4	42	49.7	49.5	35.2
Peak air gap flux density B_{g0} [T]	0.91	0.81	0.78	0.75	0.76
Peak stator yoke flux density B_{ysm} [T]	1.1987	1.1948	1.1987	1.1984	1.1948
Number of pole pairs N_p	43	55	64	80	150
Generator output frequency [Hz]	96.0	97.1	107.1	143.1	225.6
Generator output phase voltage [V]	532	888	1501	2532	7164
Generator output phase current [A]	509	599	712	707	503
Stator resistance [pu]	0.0267	0.0189	0.0131	0.0105	0.009
Synchronous inductance [pu]	0.65	0.53	0.55	0.57	0.63
Current density [A/mm^2]	5.80	4.39	3.84	3.99	4.19
Full load generator efficiency [%]	96.15	97.32	97.91	98.12	97.82
Full load system efficiency [%]	92.04	93.15	93.71	93.92	93.62
Generator material weight [Ton]					
Iron	0.98	1.66	2.97	3.72	5.55
Copper	0.23	0.55	1.01	1.25	1.95
PM	0.07	0.25	0.37	0.42	0.73
Active material	**1.27**	**2.46**	**4.34**	**5.40**	**8.24**
Gearbox	**1.28**	**4.25**	**15.5**	**36.4**	**159**
Generator construction	**0.97**	**2.58**	**6.07**	**10.68**	**24.05**
Total weight	**3.53**	**9.29**	**25.91**	**52.45**	**191.8**
Component cost [kEuro]					
Generator active material	9.15	23.14	38.31	46.90	75.34
Generator construction	4.85	12.88	30.35	53.42	120.24
Single-stage gearbox	7.70	25.51	93.03	218.2	957
Power electronic converter	30	60	120	200	400
Electrical subsystem	28.36	56.78	113.65	189.83	378.47
Generator system cost	**80.07**	**178.3**	**395.3**	**708.3**	**1931**
Cost per kilowatt [Euro/kW]	**106.8**	**118.9**	**131.8**	**141.7**	**193.1**
Annual energy					
Copper loss [MWh]	84	126	166	254	494

Iron loss [MWh]	55	76	149	242	768
Converter loss [MWh]	110	234	451	809	1768
Gearbox loss [MWh]	71	145	295	460	951
Total loss [MWh]	319	582	1061	1766	3979
AEP [GWh]	**3.32**	**7.04**	**13.70**	**23.75**	**52.07**
AEP per cost [kWh/Euro]	**41.50**	**39.49**	**34.65**	**33.52**	**26.97**

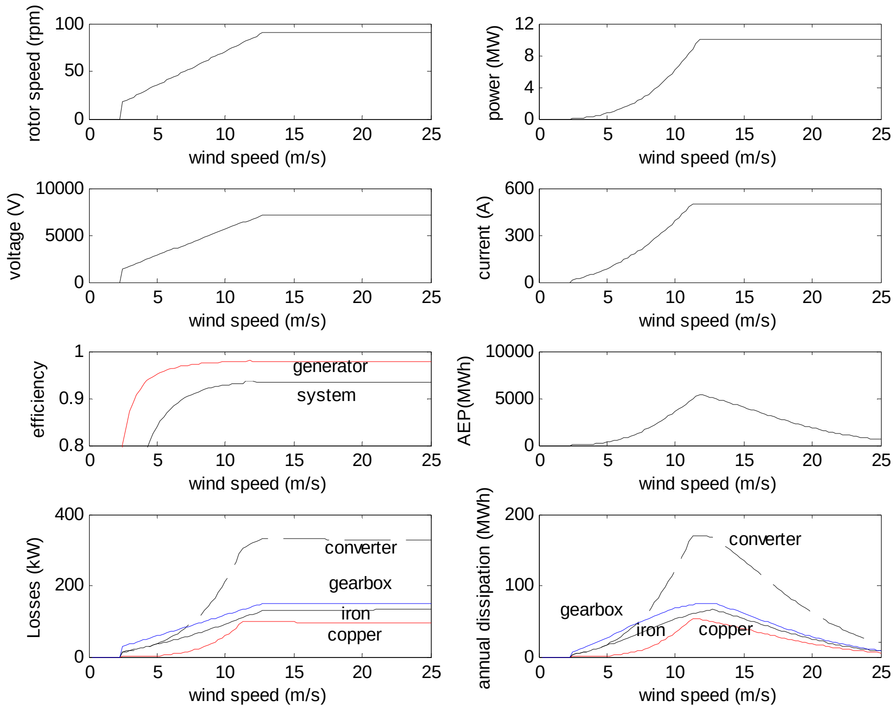
In order to further show the operational performances of PM wind generator systems with the optimized single-stage gearbox, as for examples of small, middle and large PMSG_1G systems, Fig. 2-26 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW PMSG_1G systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW PMSG_1G



(b) 3.0-MW PMSG_1G



(c) 10.0-MW PMSG_1G

Fig.2-26：*The characteristics of the PMSG_1G system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and the annual energy dissipation are also shown in Fig. 2-26. In this concept, it can be seen that the largest part of the losses is losses in the converter, which is over 40% of the annual dissipation in the generator system. In addition, the losses in the single-stage gearbox are also over 20% of the annual dissipation. Furthermore, the iron losses in the generator are also high due to the relatively high generator output frequency.

In this subsection, the PMSG_1G systems are optimized by the given gear ratios, and the PM wind generator systems with the optimum gear ratio are also investigated. By comparison of the optimization results of PM wind generator systems with the single-stage planetary gearbox, the following conclusions may be drawn:

•PM wind generator system with a single-stage gearbox has lower cost than the direct-drive system. As turbine sizes increase, a much wider range of gear ratios may adopt. The larger power ratings, the more reasonable it seems to use a higher gear ratio to adapt a reasonable size generator.
•As the wind turbines sizes increase, the single-stage gearbox cost increases, and the generator cost including the active material and the generator structure may not important. However, the single-stage gearbox cost rapidly increases than that the energy production increases when the rated power is at 5MW or higher, so that the decrease of the AEP per cost is rather large.

2.5 Design optimization and comparison of PMSG_3G systems

In this subsection, firstly, the weight and cost of the three-stage gearbox are presented at different power levels. Next, the design optimization and comparison of the PMSG_3G systems are investigated for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW, respectively.

2.5.1 Weight and cost of the three-stage planetary gearbox

In the three-stage gearbox, the weight is calculated as a linear function of the low speed shaft torque, which can be given in section 3 of the report 1. The specific cost estimate is given in Table 1-3. In order to demonstrate the gearbox weight models, Fig. 2-27 depicts the three-stage gearbox weight function of the rated power and some weight data from commercial wind turbine products. In the typical data, the right value stands for the rated power and the left value stands for the weight of the three-stage gearbox. As it can be seen, the used gearbox weight function has a good agreement with the practical data [22].

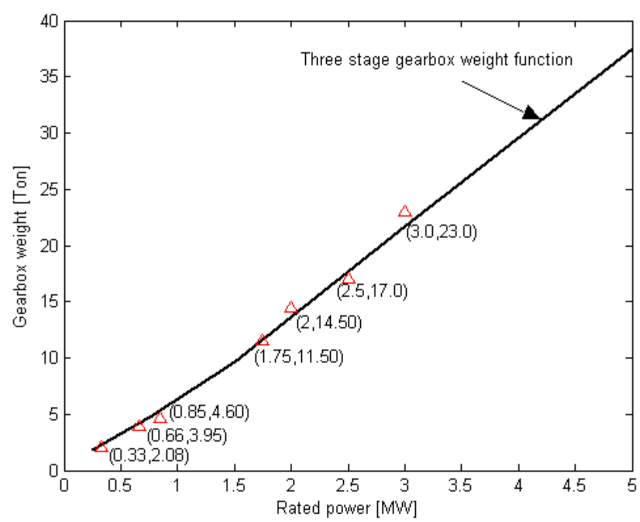


Fig.2-27： *The weight function of a three-stage gearbox and some typical weight data*

2.5.2 Optimization results and comparisons

The PMSG systems with the three-stage gearbox are also optimized by the IGA, in which the gear ratio is given to make the rated generator speed of 1200rpm in order to make a suitable comparison of DFIG_3G system. The cost, weight, size, efficiency and AEP per cost of the optimized PMSG_3G systems are compared graphically as the following, respectively.

1. Generator system cost

Fig.2-28 depicts the generator system cost function for each power level. In order to see the component cost at different rated powers, the cost of the generator active material, the generator structure, the three-stage gearbox and the power electronic converter are also shown in Fig. 2-28.

The results show that the three-stage gearbox cost and the power electronic converter cost are the main components of the generator system cost with the turbine sizes increase. The three-stage gearbox cost increase almost linearly with the rated power, however, it may rise more rapidly when the rated power exceeds 5MW, so that the generator system cost increase rapidly from 5-MW to 10-MW.

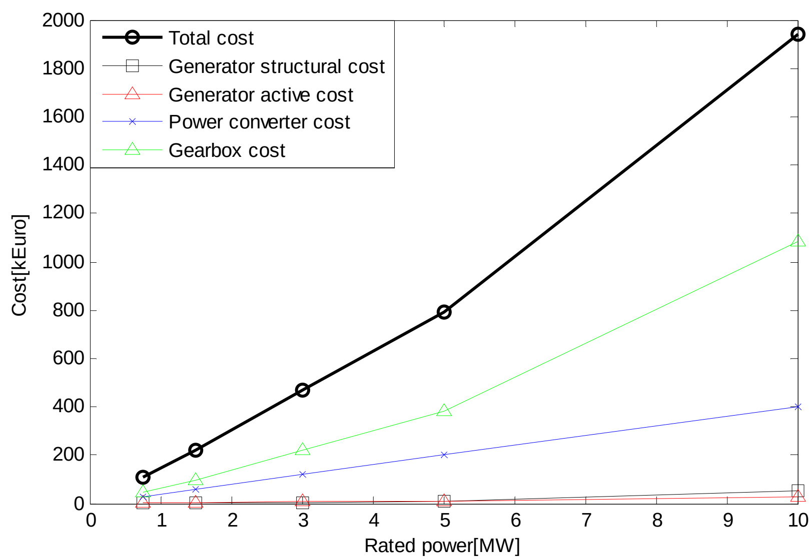


Fig.2-28： *The PMSG_3G system cost as a function of rated power*

2. Generator system weight

The generator system weight including the active material part and the three-stage gearbox are shown in Fig.2-29. It can be seen that the three-stage gearbox is the main component of the generator system weight.

3. Generator size

The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 2-30. It can be seen that the outer diameter and the length increases with increasing rated power, but the increase of the outer diameter is rather small. For example, as for the large PM generator system of 10-MW, the stator outer diameter may be only about 1.6m.

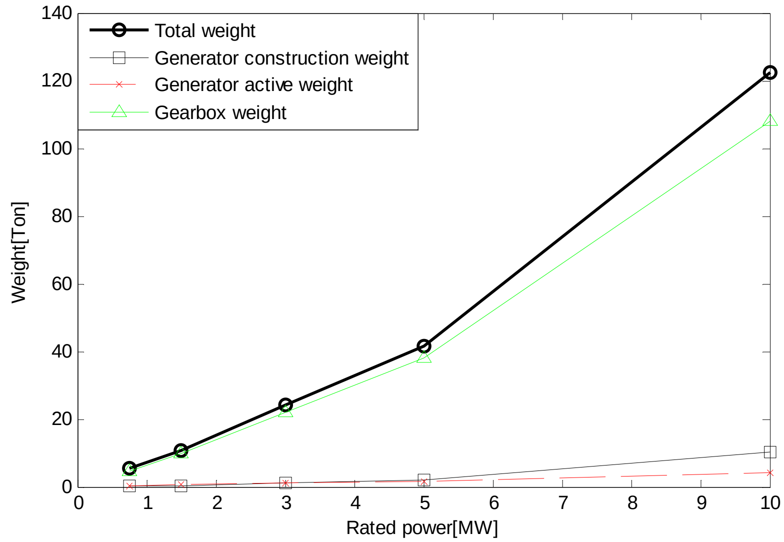


Fig.2-29：*The weight of the PMSG_3G as a function of the rated power*

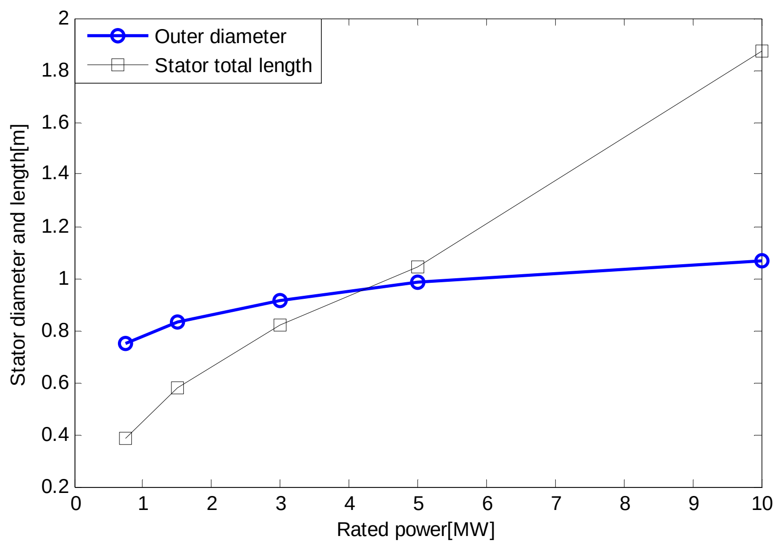


Fig.2-30：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the losses in the power electronic converter and the three-stage gearbox at rated load of the optimized PMSG_3G systems are shown in Fig. 2-31. Because the rated generator speed is at 1200rpm, the generator efficiency is high, for example, the generator efficiency increases from 97.2 % for a 0.75-MW generator to 98.6 % for a 10-MW. Due to the losses in the three-stage gearbox and the power electronic converter, the system efficiency at rated load is about 6 percent lower than the generator efficiency.

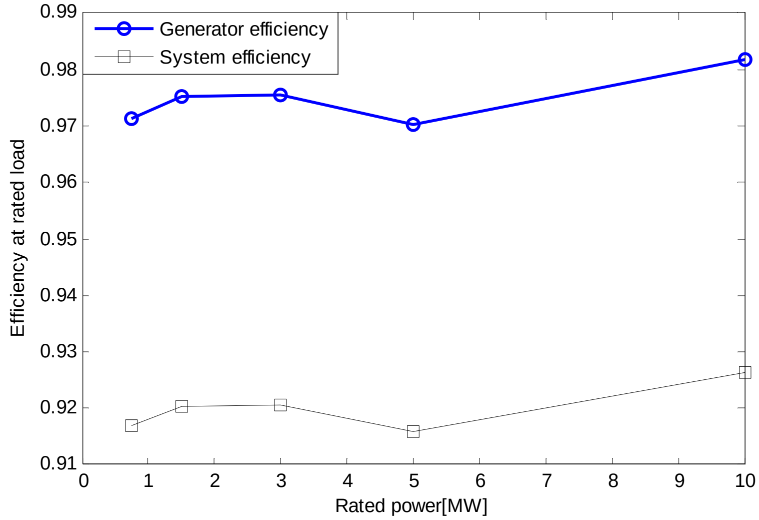


Fig.2-31：*The efficiency at full load as a function of rated power*

5. AEP per cost

The annual energy production is also calculated according to the annual average wind speed at the hub height for each power level. Fig. 2-32 depicts the AEP per cost as a function of the rated power.

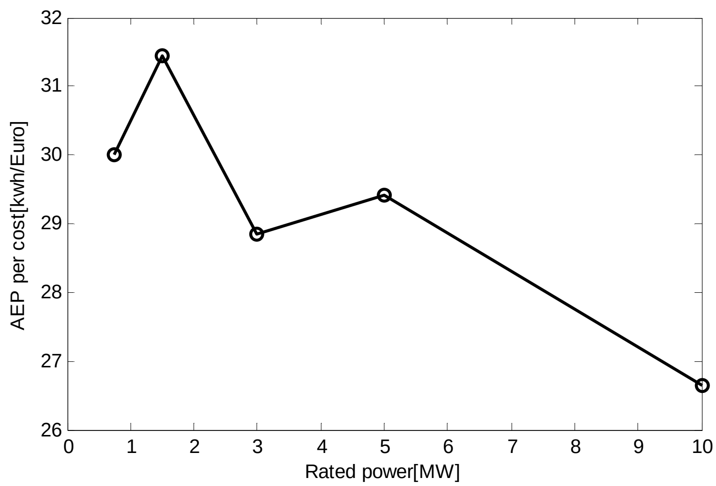


Fig.2-32：*The AEP per cost as a function of rated power*

The results shown the rated power of the most cost-effective PMSG_3G systems may be around 1.5MW, when the rated power is larger than 1.5MW, the AEP per cost decreases as the power ratings increase, but the decrease is rather small.

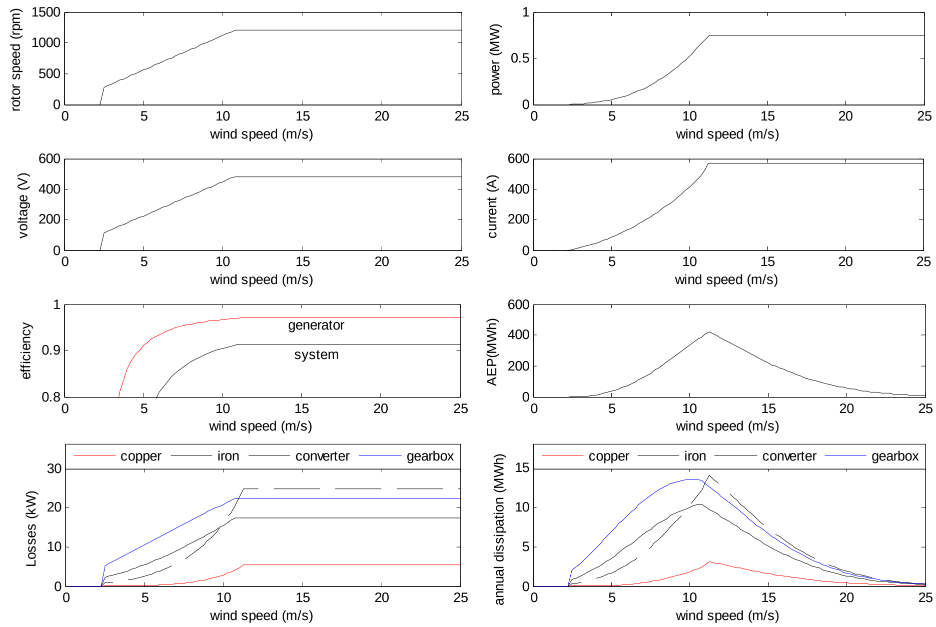
As a design reference of the PM generator with the three-stage gearbox, Table 2-5 summarizes the system important dimensions and performances resulting from each optimal design.

Table 2-5: *Main Performances of the optimized PMSG_3G systems*

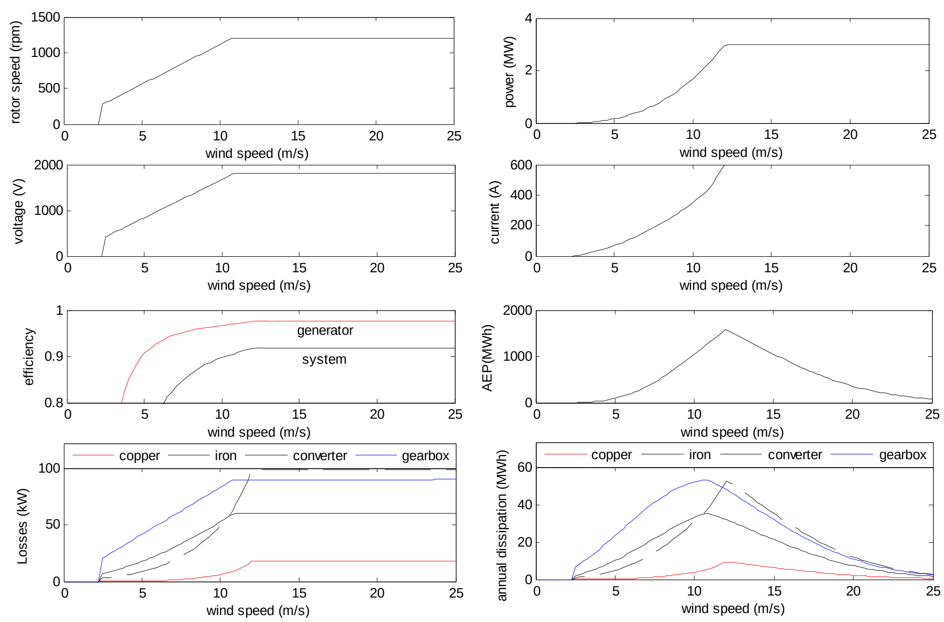
Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter *D* [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.2	11.3	12.0	12.1	11.7
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Given gear ratio	41.96	58.54	75.00	81.1	120.0
PM generator system dimensions and electrical performances					
Generator rated rotor speed [rpm]	1200	1200	1200	1200	1200
Air gap diameter D_{i1} [m]	0.58	0.68	0.76	0.84	0.86
Stator length *L* [m]	0.28	0.47	0.71	0.94	1.70
Pole pitch *Tp* [mm]	55.3	57.9	58.3	52.0	87.2
Stator slot height h_s [mm]	70.5	60.6	60.5	60.3	78.7
Stator slot width b_s [mm]	8.5	8.9	9.0	7.9	13.5
Stator tooth width b_d [mm]	10.4	10.9	10.9	9.7	16.5
Stator yoke height h_{ys} [mm]	15.7	14.3	16.1	13.7	24
Rotor yoke height h_{yr} [mm]	15.7	14.3	16.1	13.7	24
Magnet height h_m [mm]	5.5	6.5	7.6	8.1	11.2
Magnet width b_m [mm]	38.7	40.5	40.8	36.4	61
Peak air gap flux density B_{g0} [T]	0.97	0.84	0.88	0.90	0.94
Peak stator yoke flux density B_{ysm} [T]	1.19	1.18	1.11	1.19	1.19
Number of pole pairs N_p	16	18	20	25	15
Generator output frequency [Hz]	320	360	400	500	300
Generator output phase voltage [V]	479	913	1800	3401	3936
Generator output phase current [A]	569	593	597	526	900
Stator resistance [pu]	0.0066	0.0069	0.0055	0.0046	0.0033
Synchronous inductance [pu]	0.6774	0.6503	0.5951	0.5859	0.5234
Current density [A/mm^2]	5.0899	6	5.9993	5.9994	4.5214
Full load generator efficiency [%]	97.14	97.52	97.54	97.03	98.17
Full load system efficiency [%]	91.69	92.04	92.06	91.59	92.64
Generator material weight [Ton]					
Iron	0.29	0.49	0.88	1.19	3.35

Copper	0.074	0.11	0.17	0.24	0.60
PM	0.015	0.034	0.068	0.11	0.27
Active material	**0.38**	**0.64**	**1.12**	**1.54**	**4.22**
Gearbox	**4.77**	**9.77**	**21.98**	**38.24**	**108**
Generator construction	**0.17**	**0.40**	**0.98**	**1.89**	**10.09**
Total weight	**5.31**	**10.81**	**24.09**	**41.67**	**122.54**
Component cost [kEuro]					
Generator active material	2.56	4.50	7.96	11.51	29.94
Generator construction	0.84	2.02	4.90	9.44	50.46
Three-stage gearbox	47.67	97.68	219.84	382.44	1082.24
Power electronic converter	30	60	120	200	400
Electrical subsystem	28.41	56.72	113.46	189.15	378.53
Generator system cost	**109**	**221**	**466**	**793**	**1941**
Cost per kilowatt [Euro/kW]	**146**	**147**	**155**	**159**	**194**
Annual energy					
Copper loss [MWh]	21	46	69	110	175
Iron loss [MWh]	99	163	358	714	907
Converter loss [MWh]	109	230	441	792	1759
Gearbox loss [MWh]	142	290	590	919	1898
Total loss [MWh]	370	729	1458	2536	4739
AEP [GWh]	**3.28**	**6.94**	**13.45**	**23.32**	**51.73**
AEP per cost[kWh/Euro]	**30**	**31.44**	**28.85**	**29.42**	**26.65**

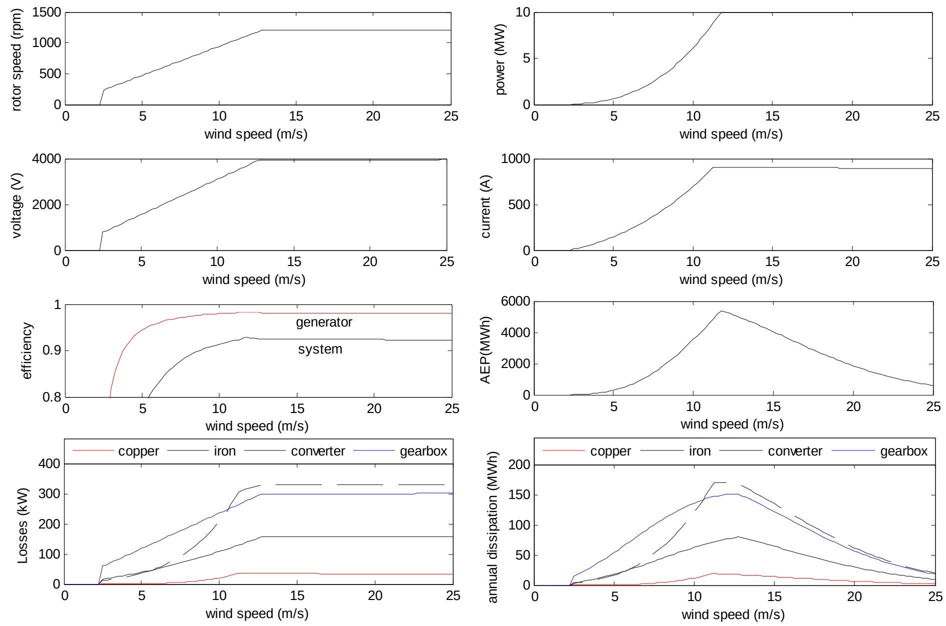
In order to further show the performances of PM wind generator systems with the three-stage gearbox, as for examples of small, middle and large PMSG_3G systems, Fig. 2-33 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW PMSG_3G systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW PMSG_3G



(b) 3.0-MW PMSG_3G



(c) 10.0-MW PMSG_3G

Fig.2-33：*The characteristics of the PMSG_3G system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and the annual energy dissipation are also shown in Fig. 2-33. In this wind turbine concept, it can be seen that the largest part of the losses is losses in the three-stage gearbox, which is almost 40% of the annual dissipation in the generator system. In addition, the losses in the converter are around 30% of annual dissipation. Furthermore, the iron losses in the generator are also high due to the high generator output frequency, which are almost 20% of annual dissipation. Compared with the above losses, the copper losses in the generator are the smallest so that they may be negligible for this wind generator system.

In this subsection, the PMSG_3G systems are optimized with different gear ratios. By comparison of the optimization results of PM wind generator systems at various rated power levels, it can be seen that the three-stage gearbox cost is the main components of the generator systems cost, the highest AEP per cost may occur around 1.5MW.

2.6 Evaluation of PMSG systems with different drive trains

In order to allow the convenient comparison and evaluation of the PM generator systems with the above different drive-train types, the concerned indexes, including the generator system cost, the annual energy yield and the AEP per cost are shown in Figs 2-34, 2-35 and 2-36, respectively. In this case, the increased or decreased percentage of the performances of PMSG_1G and PMSG_3G systems are also presented in comparison with the PMSG_DD system.

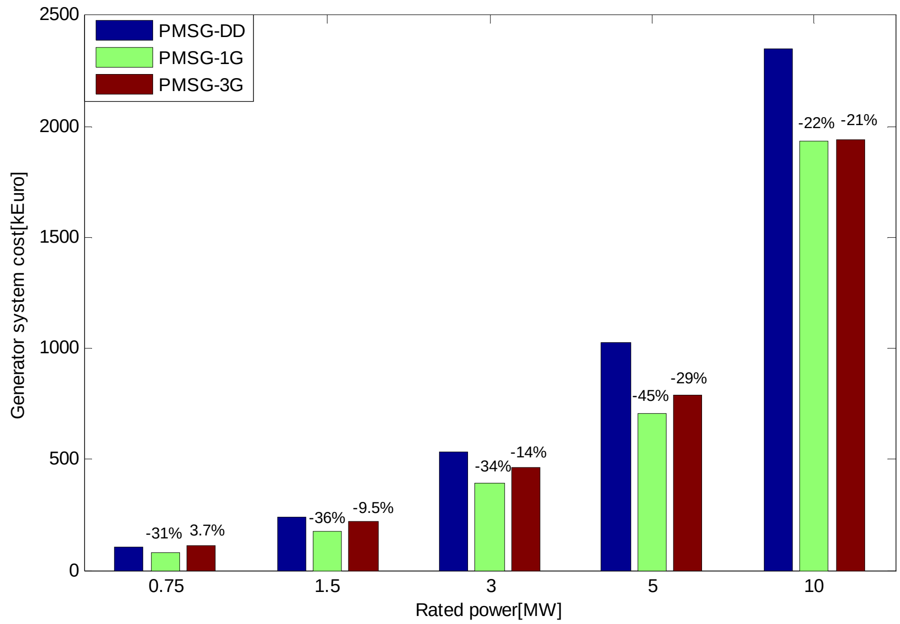


Fig.2-34：*The comparison of the generator system cost for various PM generator systems*

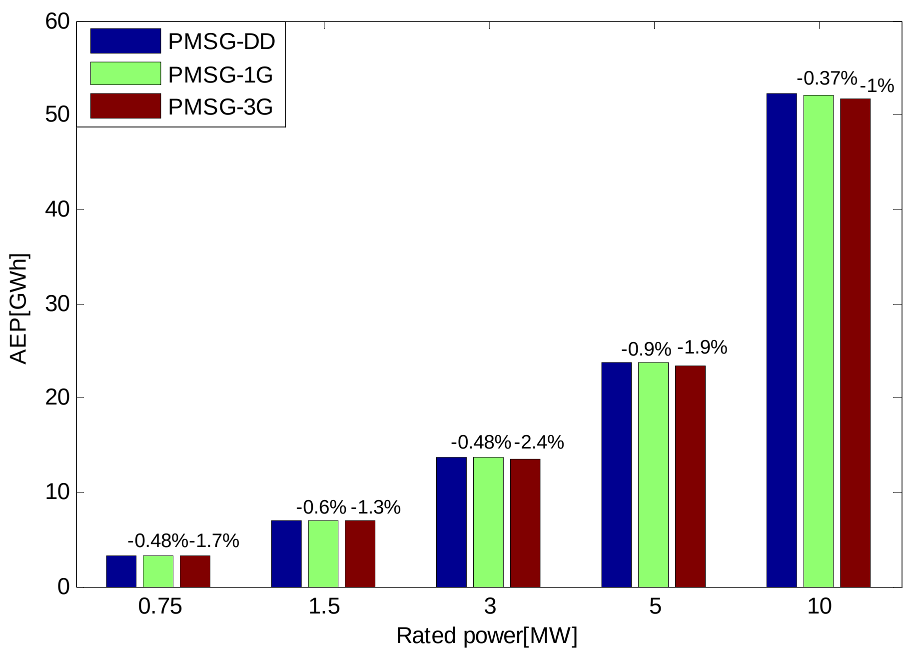


Fig.2-35：*The comparison of the annual energy yield for various PM generator systems*

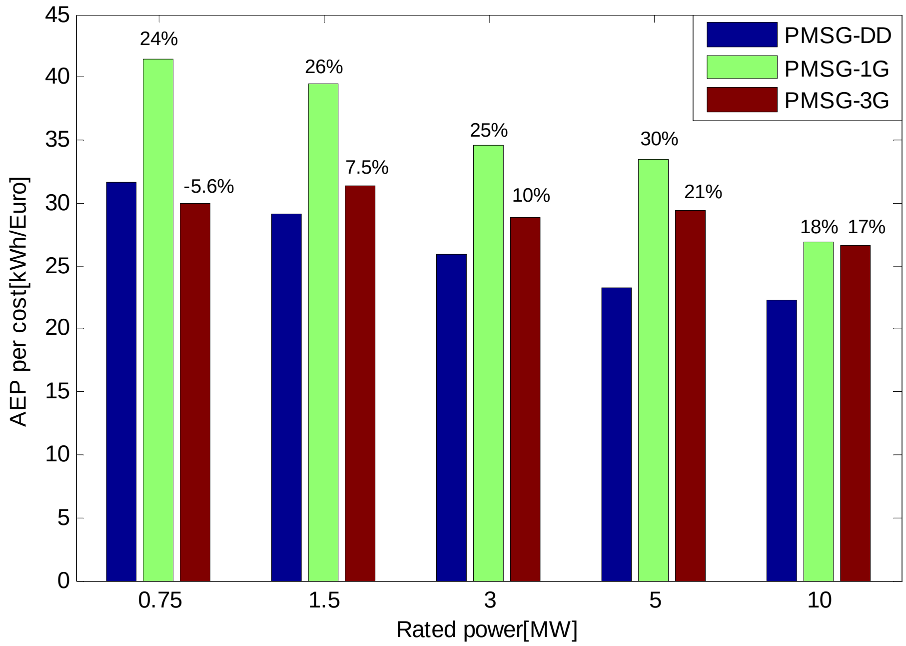


Fig.2-36：*The comparison of the AEP per cost for various PM generator systems*

It can be seen that the PMSG_DD system appears to be the most expensive alternative. Compared with the PMSG_DD system, due to using a single-stage gearbox, the generator active material cost and the generator structural cost can be reduced, so that the cost of the PMSG_1G system could be reduced over 33% on average. Similarly, due to using a three-stage gearbox, the cost of the PMSG_3G system could be reduced around 14% on average. In addition, when the rated power increases towards 10-MW, the cost of the single-stage gearbox is as much as the three-stage gearbox due to the high input torque of the single-stage gearbox, so that the cost of the PMSG_1G system maybe more expensive than that of the PMSG_3G system.

The PMSG_DD system has the highest energy yield due to the high efficiency of the drive train. Compared with the PMSG_DD system, due to the losses in the gearbox, the AEP of the PMSG_1G system could be reduced around 0.56%, and the AEP of the PMSG_3G system could be reduced over 1.5% on average. However, due to the high cost of the PMSG_DD system, the AEP per cost is low. From the Fig. 2-36, it can be seen that the PMSG_1G system increases over 24%, and the PMSG_3G system increases over 9.5% in comparison with the PMSG_DD system.

From the above numerical evaluation of the PMSG system with different drive-train concepts, it could be a good solution to reduce the cost of the large direct-drive PM generator by integration a gearbox. When the rated power is less than 5MW, the PMSG_1G system appears to the cheapest solution, however, with the rated power further increase, the cost of PMSG_3G system may be cheaper than that of the PMSG_1G system, this is because the cost of the single-stage gearbox rapidly increase under the condition of the larger output torque of gearbox. Furthermore, the annual energy yield of the PMSG_1G system is higher than that of the PMSG_3G system due to the losses in the three-stage gearbox. Therefore, the PMSG_1G have the highest performance in the AEP per cost. However, when the rated power increases towards 10-MW, the PMSG_3G system may be more cost-effective.

2.7 Summary

In this section, the three PM wind generator systems are investigated, including the direct-drive system, the single-stage gearbox drive train and the three-stage gearbox drive train. The basic characteristics of the different wind turbine concepts are briefly described. The optimization models and some assumptions are presented. The analytical models and the optimization method are demonstrated by applying to a 500-kW direct-drive PMSG system. In addition, the weight models of the single-stage and the three-stage gearbox are also demonstrated with some data from the practical gearbox. The optimization designs have been implemented for each type at the rated power of 0.75-MW, 1.5-MW, 3-MW, 5-MW and 10-MW, respectively. Furthermore, the performances of the PMSG_1G system are also investigated by giving the different gear ratio. Finally, the optimization results of the different wind generator systems are evaluated and analyzed. As for the three wind generator systems, the PMSG_DD system has the highest energy yield; however, it is also the most expensive, so that the AEP per cost may be the lowest. The PMSG_1G is an interesting alternative in terms of the generator system cost and the AEP per cost when the rated power is less than 5MW. When the rated power increases towards 10-MW, the PMSG_3G system may be the most cost-effective alternative.

3. Design optimization of EESG systems

The goal of this section is to investigate the direct-drive wind turbine with electricity excited synchronous generator (EESG) systems. The section 3 outline is as follows:

3.1 Description of direct-drive EESG (EESG_DD) systems: This subsection introduces the advantage and disadvantage of EESG_DD system. The largest size from manufactures on the current market also described.

3.2 Optimization models of EESG_DD systems: This subsection summarizes the optimized variable, the objective function and the mechanical constraints of electromagnetic design of EESG.

3.3 Design optimization and comparison of EESG_DD systems: This subsection summarizes the optimization results of EESG_DD systems for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size, efficiency and annual energy production (AEP) per cost of EESG_DD are compared and analyzed.

3.4 Summary: This subsection summarizes the evaluation of direct-drive EESG systems.

3.1 Description of direct-drive trains

The EESG is usually built with a rotor carrying the field system, provided with a DC excitation. The stator carries a three-phase winding quite similar to that of the induction machine. The rotor may have salient poles, or may be cylindrical. Salient poles are more usual in low speed machines, and may be the most useful version for application to wind turbine generators. The grid connection scheme of an EESG for direct-drive wind turbine is shown in Fig. 3-1.

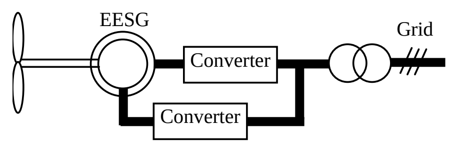


Fig. 3-1: *Scheme of a direct-drive EESG system (EESG_DD)*

All power of the generator is processed through a power electronic converter, the interface between generator and grid. At the generator side of the converter, amplitude and frequency of the voltage can be fully controlled by the converter, independently of the grid characteristics. The generator speed is fully controllable over a wide range, even to very low speeds. The gearbox can thus be omitted. The generator is directly driven by the turbine, hence the denomination ‘direct drive’. This is advantageous because the gearbox normally has a non-negligible manufacturing cost, generates some acoustic noise, requires regular maintenance (lubrication) and is also a potential cause of mechanical failure. In addition, the other advantage is that the converter permits very flexible control of the entire system. The generator speed, active and reactive power can be fully controlled in case of normal and disturbed grid conditions. Compared to the PMSG, the EESG has opportunities for control of the flux, thus allowing minimizing loss in different power ranges [16] [23]. Furthermore, it does not require the use of permanent magnets, which would represent a large fraction of the generator costs, and might quickly suffer from performance loss in harsh atmospheric conditions. Therefore, in present, it is the mostly used generator type by manufacturers for direct-drive wind turbines. The typical manufacturer is Enercon, the largest capacity of the direct-drive EESG has been up to 4.5MW (E-112, see Fig. 3-2) in the current market [24].

Fig. 3-2: *Enercon E-112, 4.5MW*

The main disadvantages are that the converter costs are considerable, as it has to process all the generator power: this requires more expensive power electronic components and needing intensive cooling. On the other hand, the generator needs a specific design: compared with normal electrical machines, it has to supply high electrical torques at low speeds. The diameter of the EESG in large wind turbines will be large. Direct-drive EESG typically has a large rotor diameter (nearly 12 m for the Enercon E-112 direct drive 4.5 MW turbine). The pole pitch must be large enough for this specific design in order to arrange space for the excitation windings and pole shoes. So the larger number of parts and windings probably makes it an expensive solution. In addition, it is necessary to excite the rotor winding with DC, using slip rings and brushes, or a brushless exciter, employing a rotating rectifier, and the field losses are inevitable.

3.2 Optimization models of EESG_DD systems

The analytical design models of EESG have been presented in section 5 of report 1. In this subsection, the optimization models of the EESG system are introduced, the assumptions and performance constraints are also presented.

1. Objective function

In order to obtain the most cost-effective EESG system, the proposed criterion includes the generator system cost

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} \quad (3\text{-}1)$$

where

$C_{g\_act} = c_{cu}\,G_{cu} + c_{Fe}\,G_{Fe}$ generator active material cost;

c_{cu}, c_{Fe} are the unit costs of the copper and the active iron, respectively;

G_{cu}, G_{Fe} are the weights of the stator and rotor copper, the stator and rotor active iron, respectively.

The meanings of other variables in equation (3-1) can be seen in the equation (2-1)

As the basis for this criterion, the different specific component costs are given in Table 1-3, respectively.

2. Optimized variables

In order to optimize the machines to the criterion (3-1), six variables are chosen to vary within a certain range, including the air gap radius (r_s), the stator length (L), the slot height (h_s), the pole pitch (τ_p), the peak air gap flux density ($\hat{B}_{g0}$) and the peak stator yoke flux density ($\hat{B}_{ys}$).

In order to make a fair and reasonable comparison with the PMSG_DD system, in this case the air gap radius of the EESG_DD system is chosen to be the same value as the PMSG_DD.

3. Assumptions and constraints

The following assumptions are used in the optimization program:

•The number of slots per pole per phase is $q = 2$. Increasing this number makes the machine heavier and more expensive because of the increasing dimensions of end-windings and yokes. Decreasing this number results in a significant increase in the excited losses, mainly in part load.

•A two-layer winding with two conductors per slot ($N_{slot} = 2$) is used to make the end windings simple due to an integer slot winding.

•The stator slots are open and a non-magnetic wedge thickness is $h_w = 5$ mm.

•The slot filling factor is set to a constant value, i.e. it is 0.65 for the stator outer diameters larger than 2m; below 2m, it is assumed to be 0.4.

•The slot width is assumed to be 45% of the slot pitch and the stator slots are skewed by one slot pitch, so that the torque ripple can be reduced.

•For mechanical reasons, the ratio of slot depth to slot width is limited within the range of 4-10, which prevents excessive tooth mechanical vibrations from occurring.

• In order to use the control mode of operation for the lowest power rating requirements on both generator and rectifier, so that it can utilize the PMSG and converter best, the values of X_s is limited to 0.5-2 pu [3].

•The air gap is equal to 0.001 of the air gap diameter; however a mechanical air gap of at least 5mm is mechanically required for the large EESG.

•The pole width b_p is kept at 70% of the pole pitch. The rotor pole shoe height at centre h_{ps} should be large enough to accommodate the damper winding, and it is assumed to be 0.1 times the pole pitch. The pole body width b_{pc} and height h_{pc} are chosen 0.4 and 0.6 times the pole pitch, respectively [20].

•The current density in the stator windings is limited to 3-6 A/mm^2, and the current loading is limited to 40-60 kA/m to prevent excessive and avoid critical cooling requirements.

3.3 Design optimization and comparison of EESG_DD systems

In order to investigate the performances of the EESG_DD system over a range of power ratings, the mentioned optimization models are used by the IGA for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size, efficiency and AEP per cost are compared graphically as the following, respectively.

1. Generator system cost

Fig.3-3 depicts the generator system costs for each optimization design. In order to see the component cost at different rated powers in this generator system, the cost of the generator active material, the generator structure and the power electronic converter are also shown in Fig. 3-3.

The results show that the generator structural cost and the active material cost are the main components of the generator system cost. The generator active material cost increase almost linearly with the rated power, however, the cost of the generator structure may rise more than linearly. Since the generator structural cost may be larger than the generator active cost when the rated power is larger than 5MW, the generator system cost increase more than linearly with the rated power.

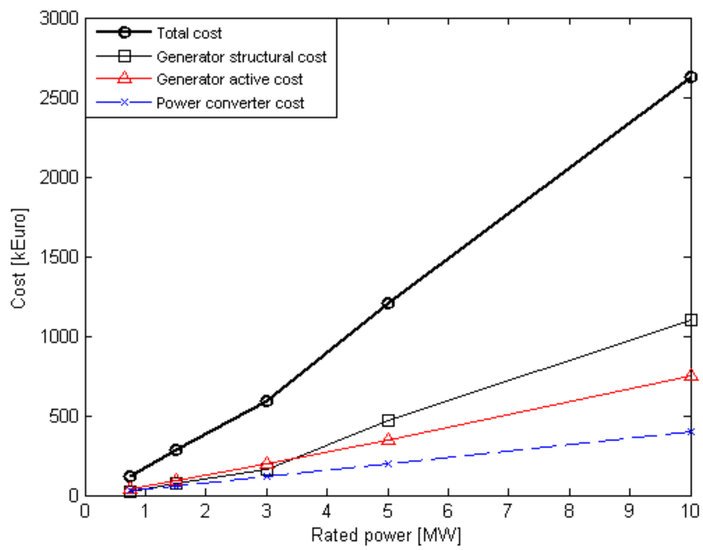


Fig.3-3： *The EESG_DD system cost as a function of rated power*

2. Generator system weight

Fig.3-4 depicts the active material weight of the direct-drive EESG systems as a function of rated power. It can be seen that the iron weight is larger than the rotor and stator copper weights, and the weight of the active materials increases slightly more than linearly.

3. Generator size

The size of the direct-drive wind generator is important. Generators will be more difficult to manufacture the larger they are, but an even more important problem might be the transportation to the site. The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 3-5. It can be seen that the outer diameter and the length increases with increasing rated power, but the increase of the outer diameter is rather larger. For example, an optimized 0.75-MW generator has an outer diameter of 2.7m and a 10-MW generator 10.2m. The corresponding stator lengths are 0.9m for the 0.75-MW generator and 2.4m for the 10-MW generator. In addition, when the rated power is larger than 3MW, the outer diameter may exceed 5.0m, so that it could lead to have a high technical difficulty of transport and assembly.

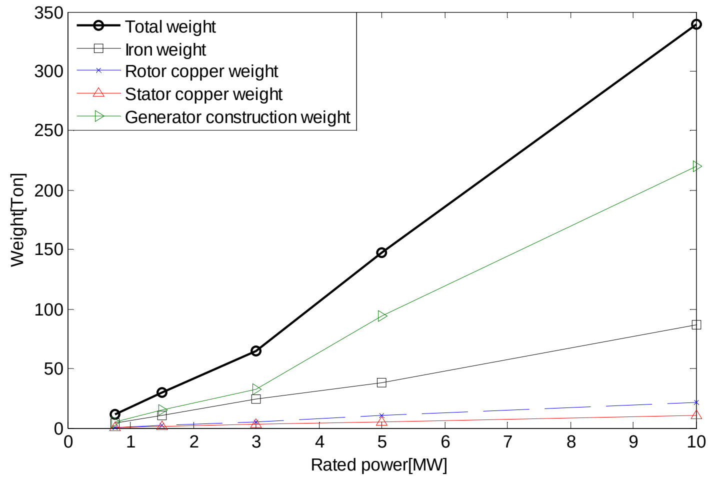


Fig.3-4：*The weight of the EESG_DD as a function of the rated power*

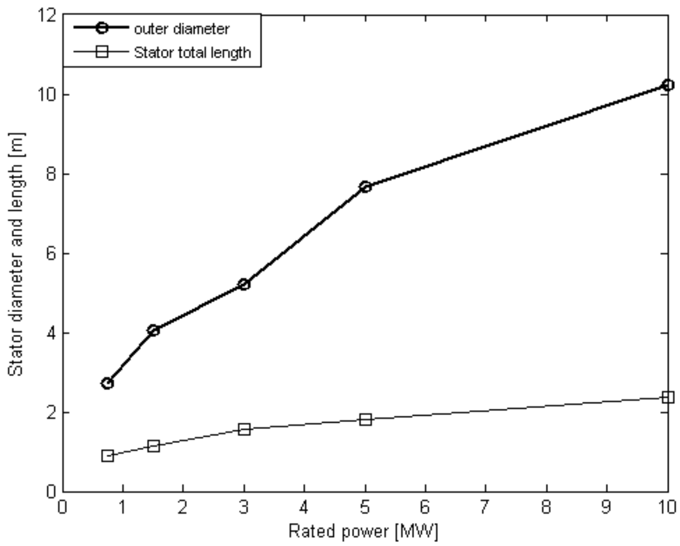


Fig.3-5：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the loss of the power electronic converter at rated load for the optimized EESG_DD system are shown in Fig. 3-6. The efficiency of the direct-drive EESG increases with the rated power, as it also does for conventional generators. In addition, the system efficiency at rated load is about 2 percent lower than the generator efficiency due to the full scale power electronic losses.

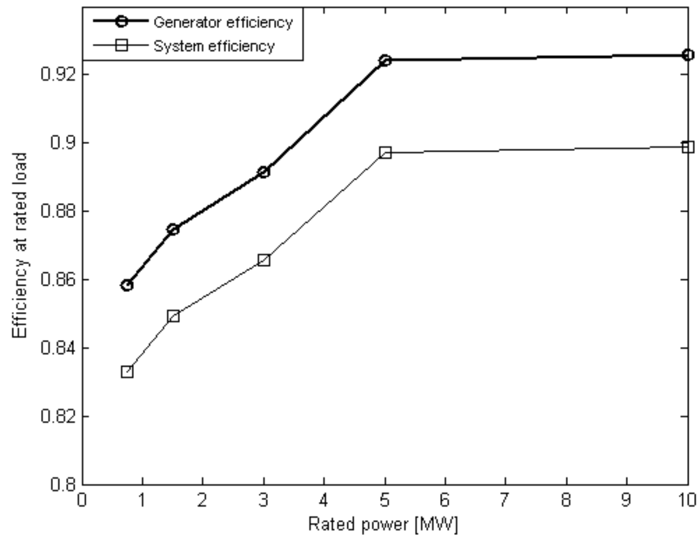


Fig.3-6：*The efficiency at full load as a function of rated power*

5. AEP per cost

In order to calculate the AEP per cost of wind generator systems, the wind site with the annual average wind speed of 7m/s at 10m height is investigated, and the corresponding mean wind speeds at the hub height for each design are given in Table 1-1. Fig. 3-7 depicts the AEP per cost as a function of the rated power. The AEP per cost is an effective index to evaluate the individual wind energy conversion, in which the cost is only considered by the generator system cost (see Fig. 3-3). The results shown the optimized EESG_DD systems have a decrease in AEP per cost as the power ratings increase.

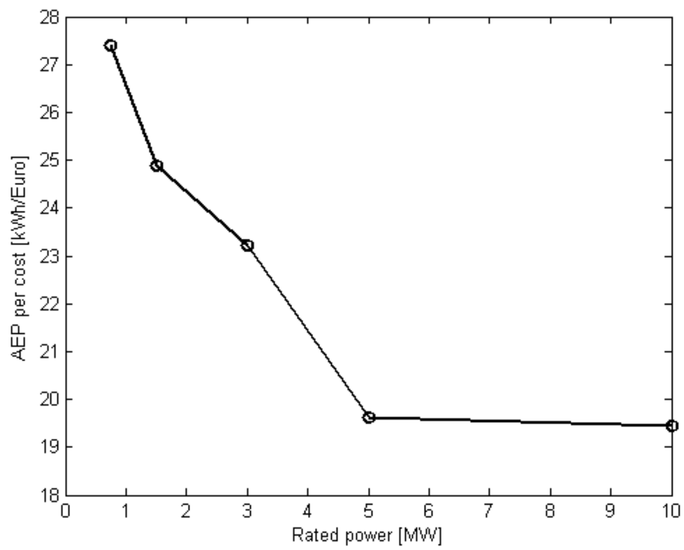


Fig.3-7：*The AEP per cost as a function of rated power*

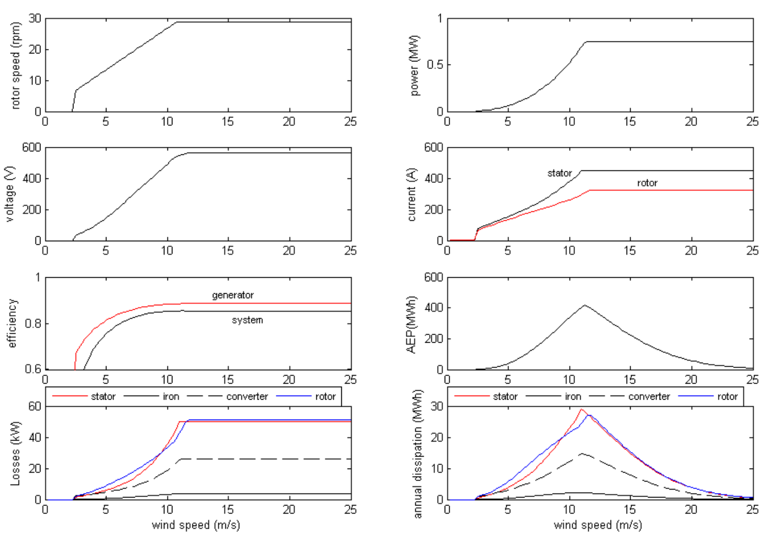
As a design reference of direct-drive EESG system, Table 3-1 summarizes the system important dimensions and performances resulting from each optimal design.

Table 3-1: *Main Performances of the optimized EESG_DD systems*

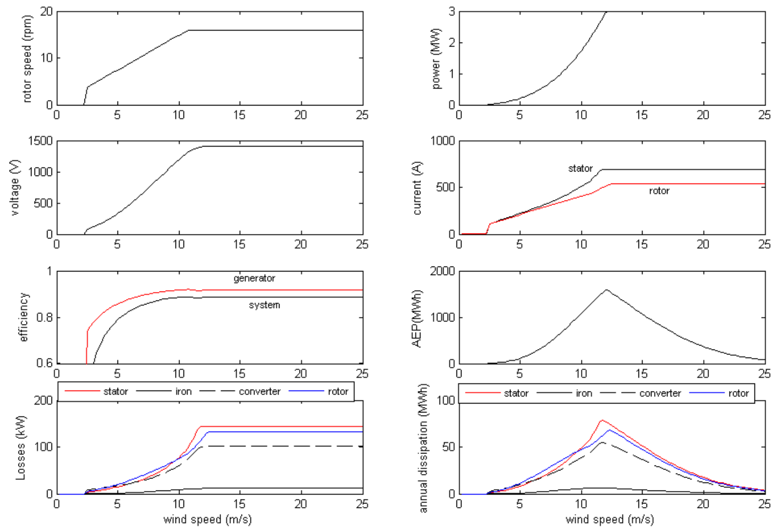
Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter D [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.6	11.6	12.3	12.2	11.8
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
EESG system dimensions and electrical performances					
Air gap diameter D_{i1} [m]	2.56	3.9	5.0	7.5	10.0
Stator length L [m]	0.71	0.90	1.30	1.50	1.98
Pole pitch Tp [mm]	90	120	137	160	191
Stator slot height h_s [mm]	55.5	56.0	66.0	59.3	72.0
Stator slot width b_s [mm]	6.8	9.0	10.0	12.0	14.3
Stator tooth width b_d [mm]	8.3	11.0	12.6	14.7	17.5
Stator yoke height h_{ys} [mm]	22.7	28.6	38.0	30.0	42.3
Rotor yoke height h_{yr} [mm]	22.7	28.6	38.0	30.0	42.3
Pole total height h_p [mm]	63.0	84.1	96.0	112.0	133.6
Pole width b_p [mm]	63.0	84.1	96.0	112.0	133.6
Peak air gap flux density B_{g0} [T]	0.95	0.89	0.96	0.71	0.83
Peak stator yoke flux density B_{ysm} [T]	1.19	1.19	1.10	1.19	1.19
Number of pole pairs	45	51	57	74	82
Generator output frequency [Hz]	21.5	17.4	15.2	18.2	13.7
Generator output phase voltage [V]	593	870	1522	2345	3645
Generator output phase current [A]	446	600	689	747	956
Stator resistance [pu]	0.063	0.061	0.045	0.047	0.038
Synchronous inductance [pu]	0.591	0.564	0.503	0.729	0.553
Current density [A/mm^2]	4.77	4.73	3.77	4.17	3.61
Full load generator efficiency [%]	85.8	87.4	89.2	92.4	92.6
Full load system efficiency [%]	83.3	84.9	86.6	89.7	89.9
Generator System material weight [Ton]					
Iron	4.6	10.6	24.1	38.5	87.2
Copper	1.7	3.9	8.2	15.3	32.3
Construction	4.8	14.9	32.3	93.9	220.4

Total weight	**11.1**	**29.4**	**64.6**	**147.7**	**339.9**
Component cost [kEuro]					
Generator active material	38.9	90.8	195	344	746
Generator construction	24.1	74.4	162	470	1102
Power electronic converter	30	60	120	200	400
Electrical subsystem	28.5	57.0	114	190	380
Generator system cost	**122**	**282**	**591**	**1204**	**2628**
Cost per kilowatt [Euro/kW]	**163**	**188**	**197**	**240**	**263**
Annual energy					
Stator copper loss [MWh]	227	468	667	1198	2219
Rotor copper loss [MWh]	240	462	640	727	1939
Iron loss [MWh]	20	31	61	93	182
Converter loss [MWh]	126	257	506	846	1887
Total loss [MWh]	613	1218	1874	2865	6228
AEP [GWh]	**3.31**	**7.02**	**13.73**	**23.6**	**51.10**
AEP per cost[kWh/Euro]	**27.25**	**24.87**	**23.22**	**19.60**	**19.44**

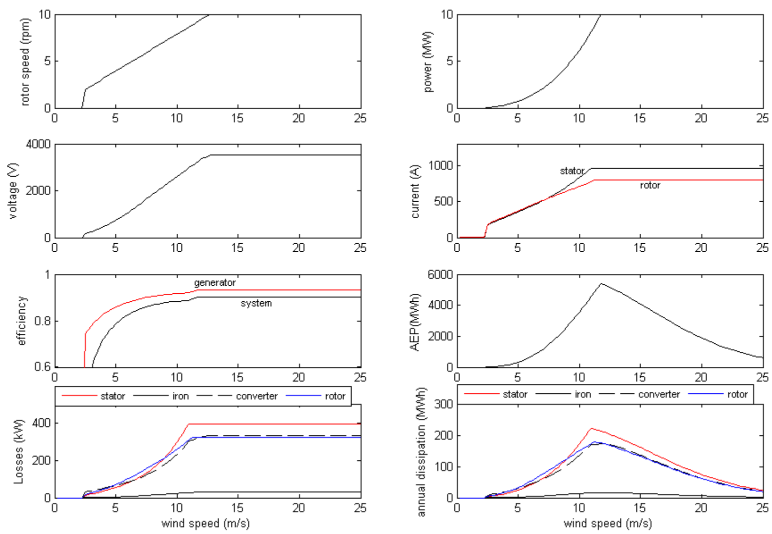
In order to further show the operational performances of direct-drive EESG system, as for examples of small, middle and large EESG_DD systems, Fig. 3-8 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW EESG_DD systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW EESG_DD



(b) 3.0-MW EESG_DD



(c) 10.0-MW EESG_DD

Fig.3-8：*The characteristics of the EESG_DD system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and annual energy dissipation are also shown in Fig. 3-8, according to the annual mean wind speed 7.0m/s at 10m height. Table 3-1 also gives the resulting the sum of annual energy yield and the annual energy dissipation. It can be seen that the main sources of the losses in this generator system are the stator copper losses, which is over 35% of the annual dissipation in the generator system. From the viewpoint of the electrical machine designs, the copper losses could be reduced by using more material, but that makes the generator more expensive. In addition, the iron losses in the generator are very small, so that they may be negligible for this wind generator system.

3.4 Summary

In this section, the direct-drive EESG system is investigated. Firstly, the basic description of this generator system is introduced. Then the optimization models and some assumptions are presented. The optimization designs have been implemented at the rated power of 0.75-MW, 1.5-MW, 3-MW, 5-MW and 10-MW, respectively. Finally, the optimization results of the EESG_DD system at different rated power levels are evaluated. From the above comparison and analysis, it can be seen that the stator outer diameter rapidly increases as turbines size increases. When the power rating of the direct-drive PM wind generator system is larger than 3MW, the outer diameter may exceed 5m, the generator structure cost may increase rapidly larger and higher than the generator active material cost, and the AEP per cost also rapidly decreases.

4. Design optimization of DFIG systems

The goal of this section is to study the wind turbines with DFIG systems, which would provide the most cost-effective alternative for the DFIG with the three–stage and the single-stage geared drive trains, respectively. The section 4 outline is as follows:

4.1 Description of the geared drive train concepts: This subsection introduces the advantages and disadvantages of the DFIG system with the three-stage gearbox (DFIG_3G). The largest size from manufactures on the current market also described. In addition, the concept of DFIG with a single-stage gearbox (DFIG_1G) is also presented.

4.2 Optimization models of DFIG systems: This subsection summarizes the optimized variables, the objective function and the mechanical constraints of electromagnetic design of DFIG.

4.3 Design optimization and comparison of DFIG_3G systems: This subsection summarizes the optimization results of DFIG_3G systems for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size, efficiency and annual energy production (AEP) per cost of DFIG_3G are compared and analyzed.

4.4 Design optimization and comparison of DFIG_1G systems: This subsection presents the optimization results of DFIG_1G systems for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW.

4.5 Evaluation of DFIG systems with different drive trains: This subsection evaluates the DFIG_3G and the DFIG_1G systems, and summarizes the results presented in Subsections 4.3 through 4.4 to allow a convenient comparison and evaluation.

4.1 Description of the geared drive trains

4.1.1 three-stage geared drive train

The doubly fed induction generator (DFIG) is the popular generator type for large wind turbines, since the rating of a power electronic converter could be reduced to roughly 30% of full scale. The connection scheme of a DFIG with a three-stage gearbox is shown in Fig. 4-1.

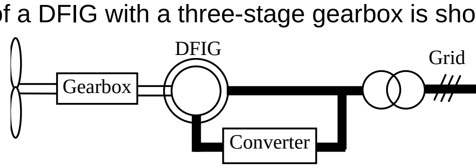


Fig. 4-1: *Scheme of a DFIG system with a three-stage gearbox (DFIG_3G)*

The stator is directly connected to the grid, while the rotor is connected through a power electronic converter. The rotor active power can be controlled by the current of the rotor side converter. Typically, by controlling the rotor active power flow direction, a speed range ± 30% around the synchronous speed can be obtained. The choice for the rated power of the rotor converter is a trade-off between costs and speed range desired. The rating of the power electronic converter is typical only 25%-30% of the generator capacity, which makes this concept attractive and popular from an economic point of view. Moreover, this converter performs reactive power compensation and smooth grid connection. There are many manufacturers, such as Vestas, Gamesa, Repower, Nordex, are using this concept on the market. The largest capacity for the commercial wind turbine product with DFIG has been up to 5MW from Repower (see Fig.4-2) [25].

Fig. 4-2: *Repower 5M-5MW*

According to the trends on the market, the variable speed pitch control concept with both DFIG and a three-stage gearbox seems to be one of the most attractive concepts, and many manufacturers have used this concept. However, the DFIG system has disadvantages as follows [22, 23, 26]:

•A three-stage gearbox is inevitable to have some drawbacks, such as heat dissipation from friction, regular maintenance and audible noise.

•The slip-ring is used to transfer the rotor power by means of a partial-scale converter, which requires a regular maintenance, and maybe result in machine failures and electrical losses.

•Under grid fault conditions, large stator peak currents may cause high torque loads on the drive train. At the same time, the insulation of winding on the rotor may also experience a stress, which may reduce the lifetime of DFIG.
•According to grid connection requirements for wind turbines, in case of grid disturbances, a ride-through capability of DFIG is also required, so that the corresponding control strategies may be complex.

4.1.2 Single-stage geared drive train

According to the advantage of the concept of the PMSG with a single-stage gearbox, the question arises whether this system with a single-stage gearbox could be used in combination with a DFIG. Because the generator torque is rather high and the speed rather low, the DFIG can be expected to have a large diameter and air gap, and therefore a high magnetizing current and high loss. However, the rating of the power electronic converter could be reduced to roughly 30%, giving an important benefit in cost and efficiency. This concept is firstly introduced by H. Plinder [8]. In this study, the optimization design and comparison of DFIG_1G system are further investigated. Fig.4-3 shows the grid connection scheme of this concept.

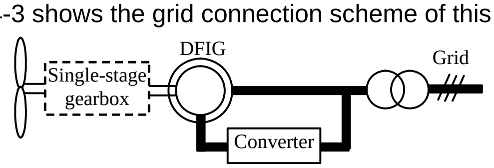


Fig. 4-3: *Scheme of a DFIG system with a single-stage gearbox (DFIG_1G)*

Compared to the traditional concept of DFIG_3G, this concept has the advantage of higher availability and operating reliability of gearbox, because most gearbox problems happen in the more sensitive high-speed stages and a well-dimensioned low-speed stage is more reliable. However, the generator design of this concept may be special due to a large number of poles for induction machines.

4.2 Optimization models of DFIG systems

The analytical design models of DFIG have been presented in section 4 of report 1. In this subsection, the optimization models of DFIG systems are introduced.

1. Objective function

In order to evaluate the most cost-effective DFIG system, the proposed criterion includes the generator system cost

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} + C_{gear} \tag{4-1}$$

where

C_{gear} three-stage or single-stage gearbox cost; the meaning of other variables can be seen in the equation (3-1).

For this criterion, the different specific component costs are given in Table 1-3, respectively.

2. Optimized variables

In order to optimize the machines to the criterion (4-1), six variables are chosen to vary within a certain range, including the air gap radius (r_s), the stator length (L), the slot height (h_s), the number of slots per pole and pole phase (q), the peak air gap flux density ($\hat{B}_{g0}$) and the peak stator yoke flux density ($\hat{B}_{ys}$). In this case, the variable of r_s for the DFIG_1G and DFIG_3G systems are chosen as the same values of PMSG systems with the same drive trains.

3. Assumptions and constraints

The following assumptions are used in the optimization program:

•The generator rated speed is assumed to be 1200rpm in the design of DFIG_3G systems at the different rated power levels.

•The gear ratios of DFIG_1G systems are set to the same values as the PMSG_1G.

•The rated slip is fixed to -0.2% at the different rated power levels of DFIG systems so that at rated rotor speed, there is still some margin for control purpose.

•A two-layer winding with two conductors per slot ($N_{slot} = 2$) is used to make the end windings simple due to an integer slot winding.

•The stator slots are open and a non-magnetic wedge thickness is $h_w = 5$ mm.

•The slot filling factor is set to a constant value, i.e. it is 0.65 for the stator outer diameters larger than 2m; below 2m, it is assumed to be 0.4.

•The slot width is assumed to be 45% of the slot pitch and the stator slots are skewed by one slot pitch.

•For mechanical reasons, the ratio of slot depth to slot width is limited within the range of 4-10, which prevents excessive tooth mechanical vibrations from occurring.

•The air gap is fixed to 1mm for DFIG_3G and 2mm for DFIG_1G in order to improve the power factor.

•In order to compare with the different wind generator systems with the same geared drive train, the air gap radius of DFIG_3G and DFIG_1G are fixed to be the same values of PMSG_3G and PMSG_1G, respectively.

•The current density in the stator windings is limited to 3-6 A/mm^2, and the current loading is limited to 40-60 kA/m to avoid critical cooling requirements.

4.3 Design optimization and comparison of DFIG_3G systems

In order to investigate the performances of the multi-stage geared drive DFIG systems over a range of power ratings, the mentioned optimization models are used to optimize the DFIG_3G systems for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The models of the three-stage gearbox are used as the same as the PMSG_3G, which have been presented in subsection 2.5. The cost, weight, size, efficiency and AEP per cost are compared graphically as the following, respectively.

1. Generator system cost

Fig. 4-4 depicts the generator system costs for each power level. In order to see the component cost at different rated powers, the cost of the generator active material, the generator structure, the three-stage gearbox, and the power electronic converter are also shown in Fig. 4-4.

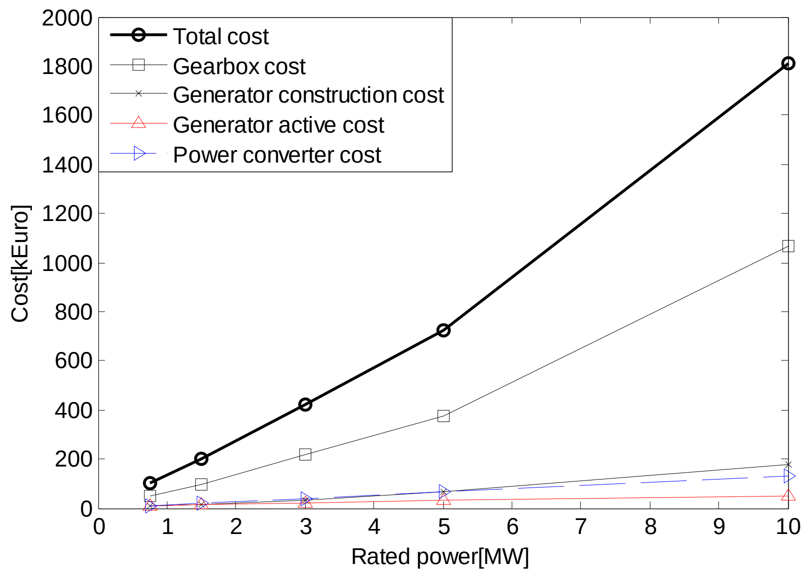


Fig.4-4： *The DFIG_3G system cost as a function of rated power*

The results show that the three-stage gearbox cost is the main component of the generator system cost. The cost of the power electronic converter is low due to the partial-scale rated power of this generator system, and the cost of the generator active materials and the generator structure are relatively low, due to the high rotor speed.

2. Generator system weight

The generator system weight including the active material part and the three-stage gearbox are shown in Fig. 4-5. It can be seen that the three-stage gearbox is the main component of the generator system weight.

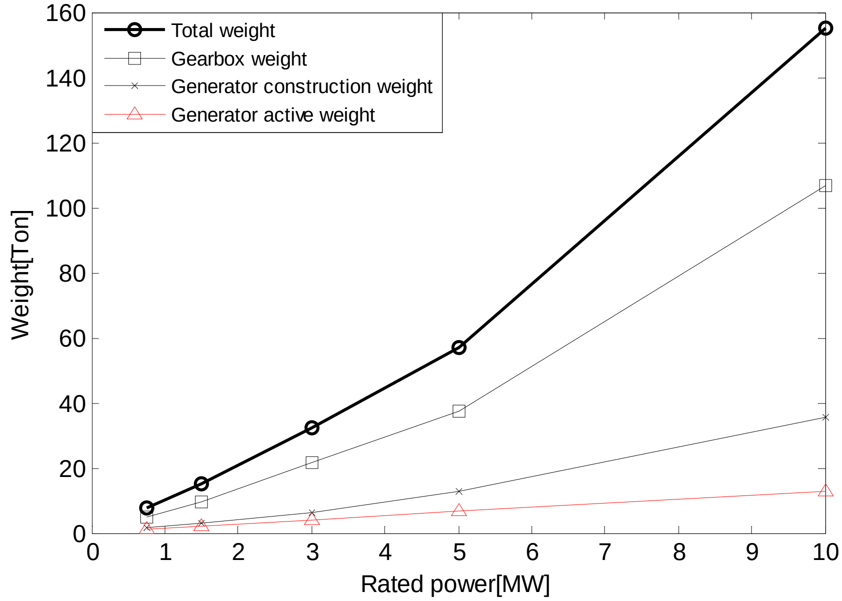


Fig.4-5：*The weight of the DFIG_3G system as a function of the rated power*

3. Generator size

The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 4-6. It can be seen that the outer diameter and the length increases with increasing rated power, but the increase of the outer diameter is rather small. For example, as for the large DFIG_3G system of 10-MW, the stator outer diameter may be only about 1.8m, and the stator total length is about 2.4m.

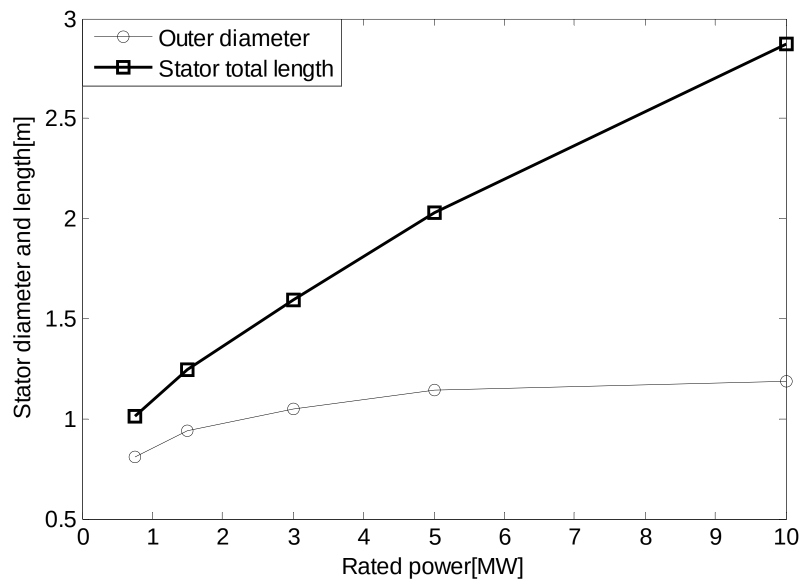


Fig.4-6：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the loss in the three-stage gearbox at rated load of the optimized DFIG_3G systems are shown in Figure 4-7. Because the rated rotor speed is at 1200rpm, the generator efficiency is high, for example, the generator efficiency increases from 94.2 % for a 0.75-MW generator to 97.6 % for a 10-MW. Due to the losses in the three-stage gearbox, the system efficiency at rated load is about 2 percent lower than the generator efficiency.

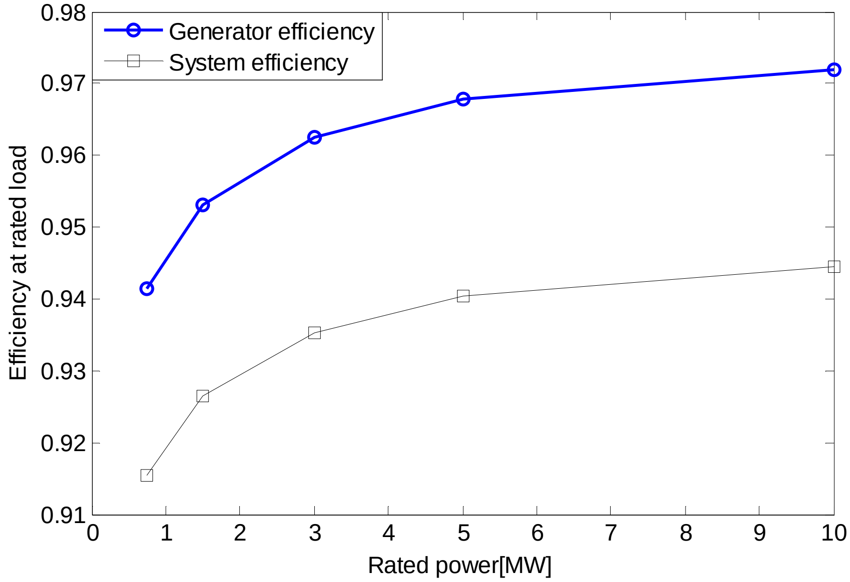


Fig.4-7：*The efficiency at full load as a function of rated power*

5. AEP per cost

The annual energy production is also calculated according to the annual average wind speed at the hub height for each design. Fig. 4-8 depicts the AEP per cost as a function of the rated power, in which the cost is considered by the generator system cost.

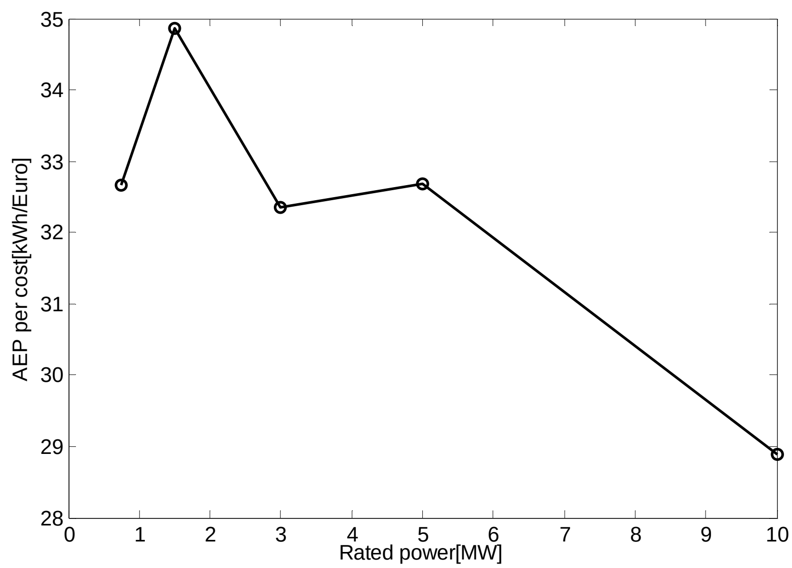


Fig.4-8：*The AEP per cost as a function of rated power*

The optimum results shown the rated power of the most cost-effective DFIG_3G system may be around 1.5MW, when the rated power is larger than 1.5MW, the AEP per cost decreases as the power ratings increase, but the decrease is rather small.

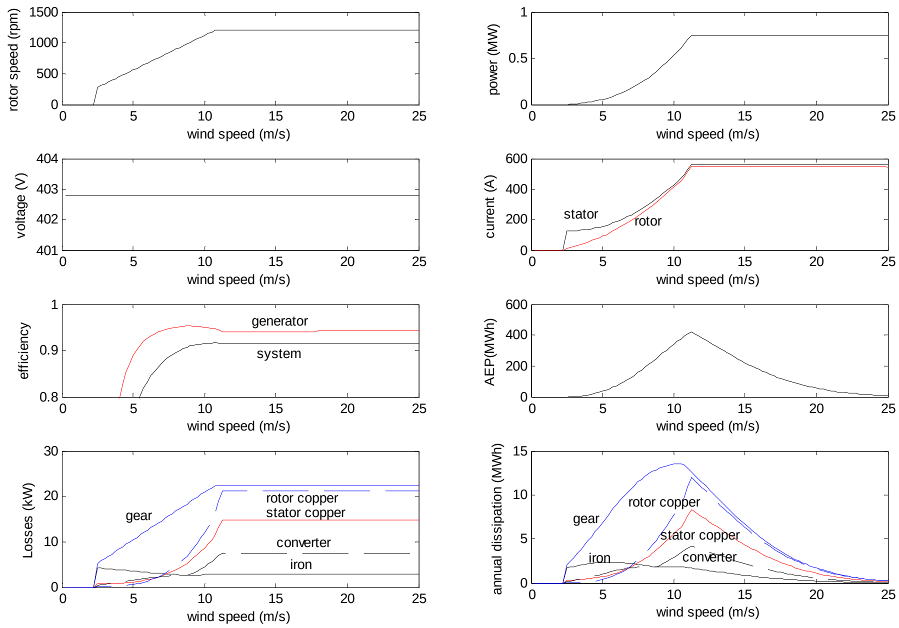
As a design reference of the DFIG_3G system, Table 4-1 summarizes the system important dimensions and performances resulting from each optimal design.

Table 4-1: *Main Performances of the optimized DFIG_3G systems*

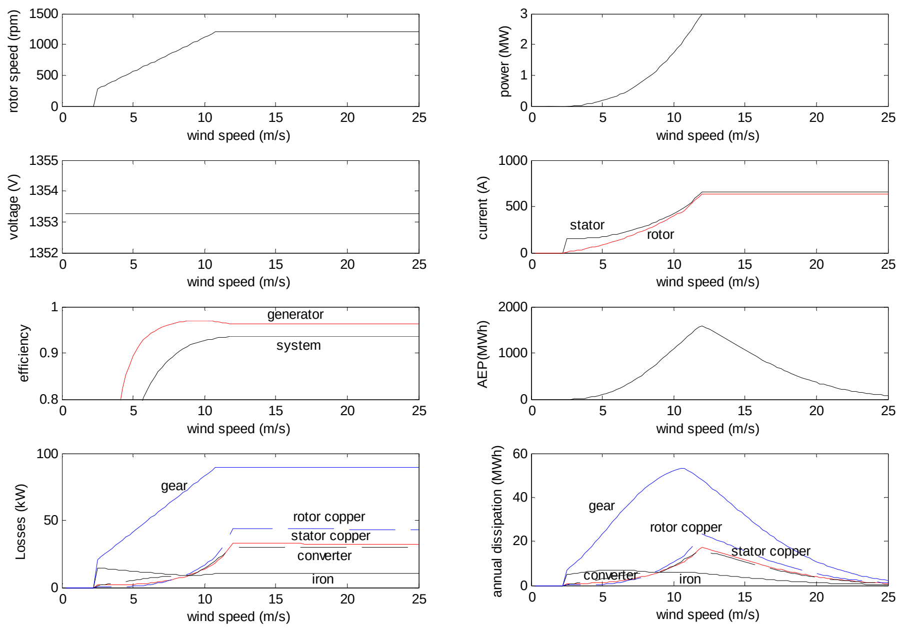
Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter D [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.2	11.2	11.9	12.0	11.6
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Given gear ratio	41.96	58.54	75.00	81.1	120.0
DFIG system dimensions and electrical performances					
Number of pole pairs N_p	3	3	3	3	3
Generator rated rotor speed [rpm]	1200	1200	1200	1200	1200
Air gap diameter D_{i1} [m]	0.58	0.68	0.76	0.84	0.86
Stator length L [m]	0.41	0.53	0.80	1.15	1.97
Pole pitch Tp [mm]	304	356	398	440	450
Stator slot height h_s [mm]	47.8	53.8	52.5	51.1	53
Stator slot width b_s [mm]	11	12.8	11.7	12.7	11.1
Stator tooth width b_{sd} [mm]	9.3	11	10.4	11.8	10.3
Stator yoke height h_{ys} [mm]	65.3	77.5	92.8	101.8	110.9
Rotor yoke height h_{yr} [mm]	65.3	77.5	92.8	101.8	110.9
Rotor slot height h_r [mm]	47.8	53.8	52.5	51.1	53
Rotor slot width b_r [mm]	7.6	9	8.5	9.6	8.4
Rotor tooth width b_{rd} [mm]	9.3	11	10.4	11.8	10.3
Peak air gap flux density B_{g0} [T]	0.81	0.82	0.88	0.86	0.92
Peak stator yoke flux density B_{ysm} [T]	1.20	1.19	1.20	1.19	1.19
Generator output phase voltage [V]	403	624	1353	2124	4620
Generator output phase current [A]	562	712	655	684	641
Stator resistance [pu]	0.022	0.017	0.012	0.0099	0.0078
Stator leakage inductance [pu]	0.097	0.096	0.073	0.060	0.052
Excited magnetic inductance [pu]	4.3776	5.1793	4.27	5.4125	3.809
Rotor resistance [pu]	0.032	0.024	0.017	0.013	0.01

Rotor leakage inductance [pu]	0.122	0.1192	0.0895	0.072	0.0642
Current density [A/mm^2]	5.97	5.70	5.92	5.85	6
Full load generator efficiency [%]	94.14	95.3	96.24	96.78	97.2
Full load system efficiency [%]	91.54	92.64	93.53	94.03	94.44
Generator material weight [Ton]					
Iron	1.04	1.86	3.56	6.06	11.43
Stator copper	0.15	0.24	0.33	0.45	0.68
Rotor copper	0.10	0.17	0.24	0.34	0.51
Active material	**1.28**	**2.27**	**4.13**	**6.84**	**12.62**
Gearbox	**4.77**	**9.73**	**21.66**	**37.28**	**106.54**
Total weight	**7.71**	**15.04**	**32.11**	**56.98**	**154.90**
Component cost [kEuro]					
Generator active material	6.82	11.69	19.26	29.93	52.14
Generator construction	8.29	15.22	31.55	64.29	178.73
Three-stage gearbox	47.67	97.26	216.64	372.84	1065.38
Power electronic converter	10	20	40	67	133
Electrical subsystem	28.5	57	114	190	380
Generator system cost	**101.28**	**201.17**	**421.46**	**723.72**	**1809.58**
Cost per kilowatt [Euro/kW]	**135**	**134**	**140**	**145**	**181**
Annual energy					
Stator copper loss [MWh]	61	96	137	202	368
Rotor copper loss [MWh]	83	132	174	256	447
Iron loss [MWh]	26	45	87	143	278
Converter loss [MWh]	34	72	139	254	557
Gearbox loss [MWh]	141	290	590	919	1905
Total loss [MWh]	346	636	1127	1775	3555
AEP [GWh]	**3.31**	**7.01**	**13.63**	**23.65**	**52.28**
AEP per cost[kWh/Euro]	**32.67**	**34.86**	**32.35**	**32.68**	**28.89**

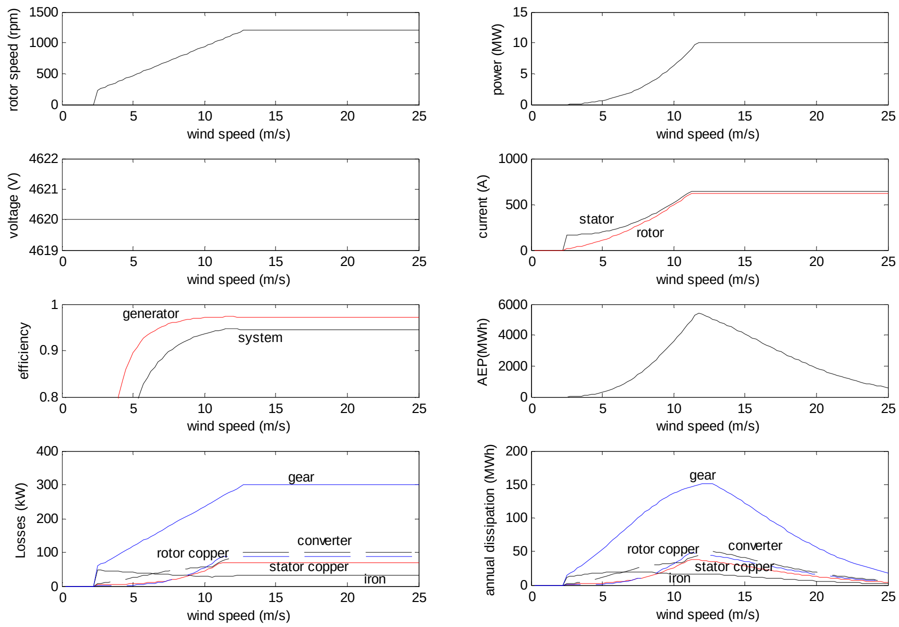
In order to further show the operational performances of the optimized DFIG_3G systems, as for examples of small, middle and large DFIG_3G systems, Fig. 4-9 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW DFIG_3G systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW DFIG_3G



(b) 3.0-MW DFIG_3G



(c) 10.0-MW DFIG_3G

Fig.4-9：*The characteristics of the DFIG_3G systems as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and annual energy dissipation are also shown in Fig. 4-9, according to the annual wind speed of 7m/s at 10m. It can be seen that the losses in the three-stage gearbox dominate the losses in this generator system. From the results in Table 4-1, roughly 60% of the annual energy dissipation in the generator system is in the gearbox.

In this subsection, the DFIG_3G systems are optimized by the given different gear ratios. By comparison of the optimization results the DFIG_3G systems at different rated power levels, it can be seen that the three-stage gearbox cost is the main components of the generator systems cost, the highest AEP per cost may occur around 1.5MW, and the largest part of the losses is losses in the three-stage gearbox in this generator system.

4.4 Design optimization and comparison of DFIG_1G systems

In the design optimization of DFIG_1G systems, the weight and cost of the single-stage planetary gearbox of the optimum PMSG_1G systems are used, which have been presented in subsection 2.4 of this report. The optimization and comparison of DFIG_1G with the given gear ratio are performed for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW, respectively. The cost, weight, size, efficiency and AEP per cost of the optimum DFIG_1G systems are also compared graphically as the following, respectively.

1. *Generator system cost*

Fig. 4-10 depicts the generator system cost function for each optimization design. In order to see the component costs at different rated powers, the cost of the generator active material, the generator structure, the single-stage gearbox, and the power electronic converter are also shown in Fig. 4-10.

The results show that the single-stage gearbox cost is the main component of the generator system cost. The cost of the power electronic converter is low due to the partial-scale rated power of this generator system, and the cost of the generator active materials and the generator structure are also relatively low, due to the relatively high rotor speed.

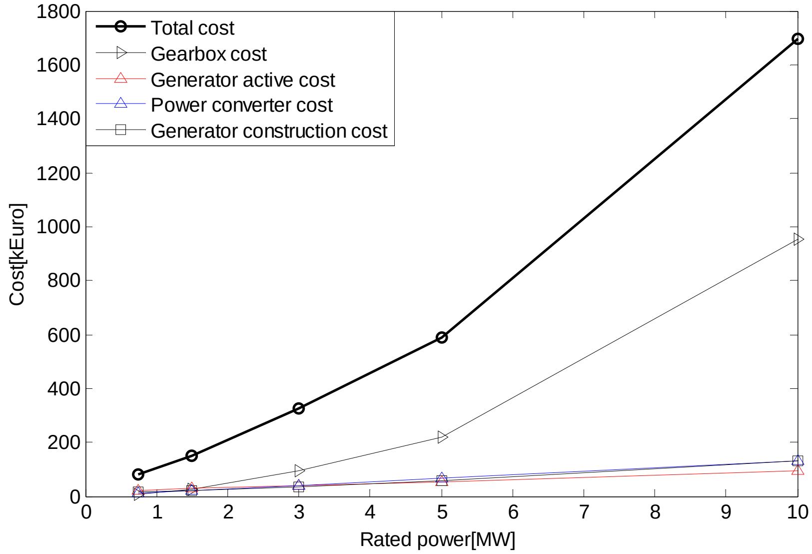


Fig.4-10： *The DFIG_1G system cost as a function of rated power*

2. Generator system weight

The generator system weight including the active material part and the single-stage gearbox are shown in Fig. 4-11. It can be seen that the single-stage gearbox is the main component of the generator system weight. In addition, the generator active weight is only a small part of the generator system. The total generator system cost still slightly increase more than linearly when the rated power is less than 5MW, however, it increase rapidly when the rated power increases towards to 10-MW, due to the gearbox weight increase rapidly.

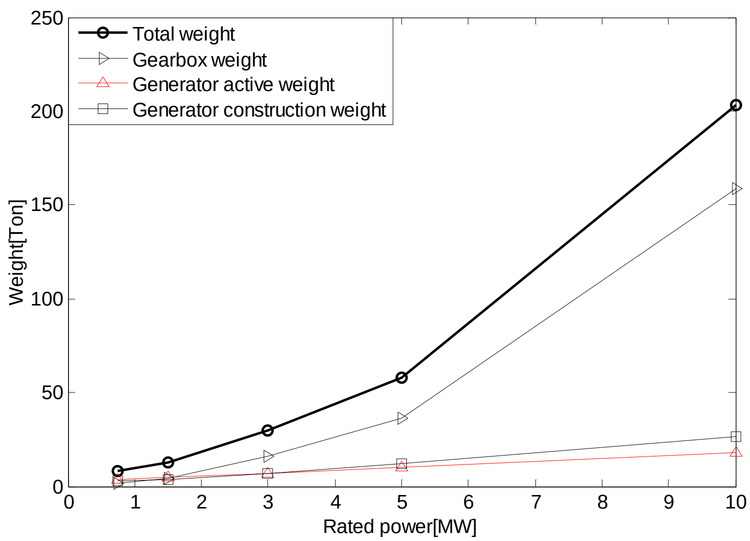


Fig.4-11：*The weight of the DFIG_1G system as a function of the rated power*

3. Generator size

The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 4-12. It can be seen that the outer diameter and the length increases with increasing rated power. Due to the relatively low generator speed, the outer diameter of the DFIG_1G system is larger than the stator total length at a given rated power.

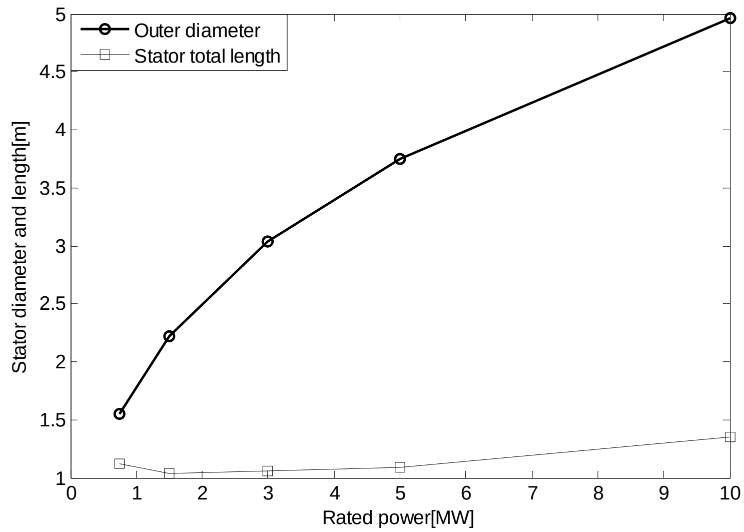


Fig.4-12：*The outer diameter and stator total length as a function of the rated power*

4. Full load efficiency

Both the generator efficiency and the system efficiency including the losses in the single-stage gearbox at rated load of the optimized DFIG_1G systems are shown in Figure 4-13. Compared with the DFIG_3G system, the generator efficiency is relatively low due to the low generator speed, for example, the generator efficiency increases from 88 % for a 0.75-MW generator to 96 % for a 10-MW. Due to the losses in the single-stage gearbox, the system efficiency at rated load is about 1.5 percent lower than the generator efficiency.

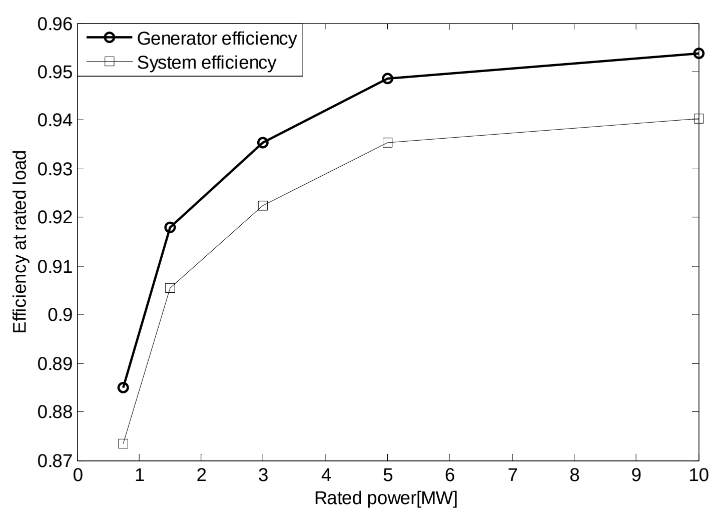


Fig.4-13：*The efficiency at full load as a function of rated power*

5. AEP per cost

The annual energy production is also calculated according to the annual average wind speed at the hub height for each design. Fig. 4-14 depicts the AEP per cost as a function of the rated power, in which the cost is considered by the generator system cost.

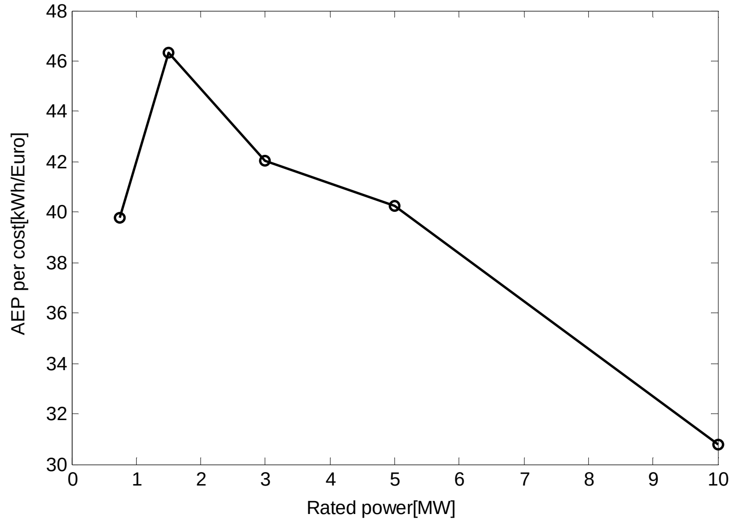


Fig.4-14：*The AEP per cost as a function of rated power*

The results shown the rated power of the most cost-effective DFIG_1G systems may be around 1.5MW, when the rated power is larger than 1.5MW, the AEP per cost decreases as the power ratings increase, but the decrease is rather small.

As a design reference of the DFIG_1G system, Table 4-2 summarizes the system important dimensions and performances resulting from each optimal design.

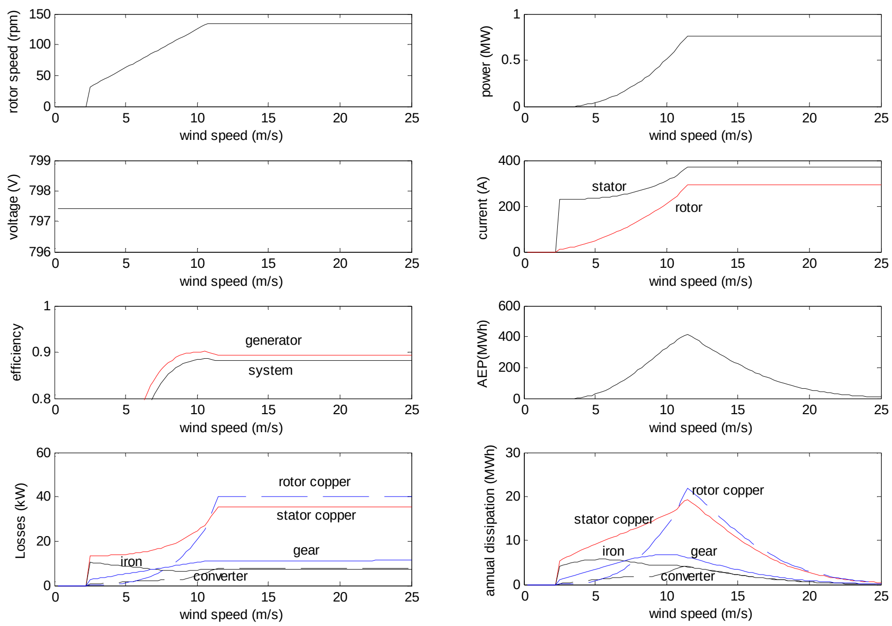
Table 4-2: *Main Performances of the optimized DFIG_1G systems*

Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter D [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.2	11.2	11.9	12.0	11.6
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Given single-stage gear ratio	4.68	5.17	6.27	7.25	9.02
DFIG system dimensions and electrical performances					
Number of pole pairs N_p	27	34	36	34	40
Generator rated rotor speed [rpm]	1343	106	100	107	90
Air gap diameter D_{i1} [m]	1.4	2.1	2.9	3.8	4.8
Stator length L [m]	0.96	0.84	0.80	0.76	0.98
Pole pitch Tp [mm]	81.4	97	129	166	189
Stator slot height h_s [mm]	56.8	38	37.9	36.8	39.1
Stator slot width b_s [mm]	6.7	5.1	4.9	6.4	7.2
Stator tooth width b_{sd} [mm]	6.8	5.7	5.6	7.5	8.5
Stator yoke height h_{ys} [mm]	16	21.1	28.1	39.4	42.2

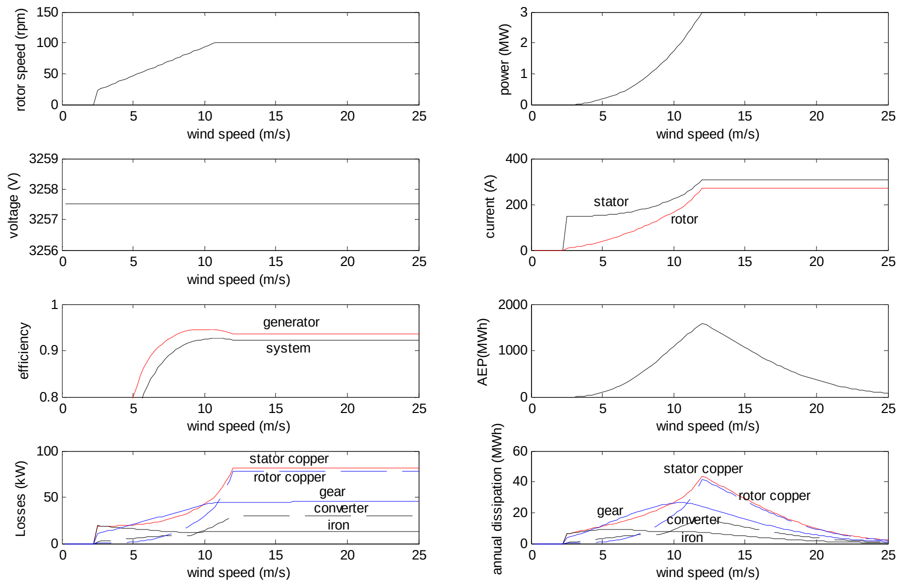
Rotor yoke height h_{yr} [mm]	16	21.1	28.1	39.4	42.2
Rotor slot height h_r [mm]	56.8	38	37.9	36.8	39.1
Rotor slot width b_r [mm]	5.6	4.7	4.6	6.1	6.9
Rotor tooth width b_{rd} [mm]	6.8	5.7	5.6	7.5	8.5
Peak air gap flux density B_{g0} [T]	0.72	0.81	0.83	0.88	0.83
Peak stator yoke flux density B_{ysm} [T]	1.16	1.19	1.19	1.19	1.18
Generator output phase voltage [V]	797	1815	3258	4068	6594
Generator output phase current [A]	407	323	315	397	469
Stator resistance [pu]	0.0435	0.0342	0.0277	0.0215	0.019
Stator leakage inductance [pu]	0.3356	0.1997	0.1542	0.1113	0.1131
Excited magnetic inductance [pu]	1.442	1.5668	1.9805	2.1881	2.8044
Rotor resistance [pu]	0.0523	0.0372	0.0294	0.0226	0.0197
Rotor leakage inductance [pu]	0.4001	0.2157	0.1628	0.1159	0.1169
Current density [A/mm^2]	5.84	5.93	6	6	5.86
Full load generator efficiency [%]	88.49	91.8	93.54	94.87	95.38
Full load system efficiency [%]	87.33	90.55	92.24	93.53	94.03
Generator material weight [Ton]					
Iron	3.04	3.59	5.50	7.87	14.45
Stator copper	0.44	0.60	0.83	1.02	1.81
Rotor copper	0.36	0.55	0.79	0.97	1.74
Active material	**3.84**	**4.75**	**7.12**	**9.87**	**18**
Gearbox	**1.38**	**4.37**	**15.76**	**36.37**	**158.65**
Construction	**2.79**	**3.72**	**6.99**	**11.86**	**26.65**
Total weight	**7.99**	**12.84**	**29.87**	**58.09**	**203.3**
Component cost [kEuro]					
Generator active material	21.16	28.13	40.81	53.58	96.62
Generator construction	13.94	18.62	34.96	59.29	133.23
Single-stage gearbox	8.14	26.21	94.54	218.2	951.9
Power electronic converter	10	20	40	67	133
Electrical subsystem	28.5	57.0	114	190	380
Generator system cost	**81.75**	**149.96**	**324.3**	**587.73**	**1695**
Cost per kilowatt [Euro/kW]	**109**	**100**	**108**	**118**	**170**
Annual energy					

Stator copper loss [MWh]	195	309	407	542	965
Rotor copper loss [MWh]	154	206	310	437	891
Iron loss [MWh]	63	77	115	168	286
Converter loss [MWh]	34	72	141	261	561
Gearbox loss [MWh]	71	145	296	459	948
Total loss [MWh]	517	809	1268	1867	3651
AEP [GWh]	**3.25**	**6.95**	**13.64**	**23.65**	**52.19**
AEP per cost[kWh/Euro]	**39.78**	**46.31**	**42.06**	**40.23**	**30.79**

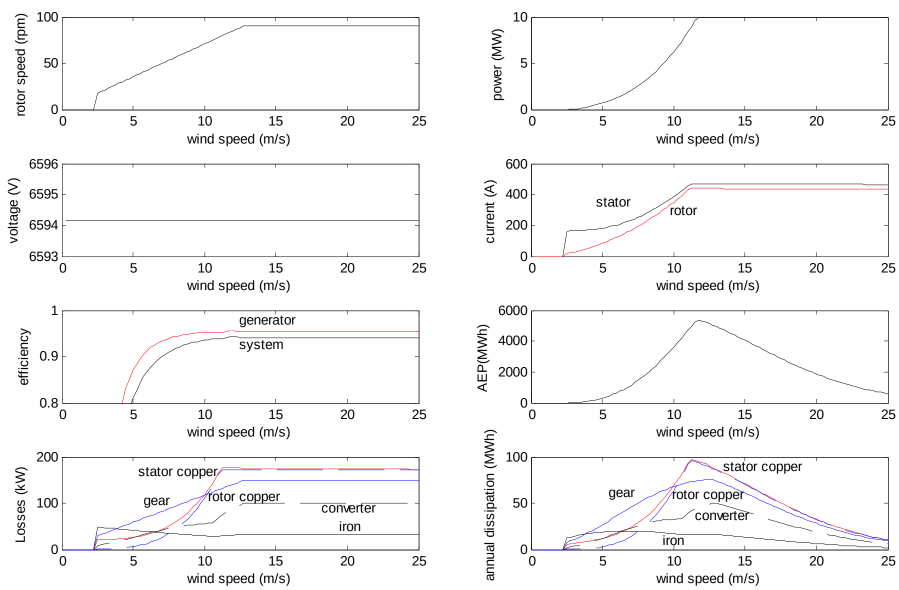
In order to further show the operational performances of the optimized DFIG_1G systems, as for examples of small, middle and large DFIG_1G systems, Fig. 4-15 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW DFIG_1G systems as a function of the wind speed: generator rotor speed, stator voltage, stator current, grid power, efficiency and losses in the generator system.



(a) 0.75-MW DFIG_1G



(b) 3.0-MW DFIG_1G



(c) 10.0-MW DFIG_1G

Fig.4-15：*The characteristics of the DFIG_1G system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and annual energy dissipation are also shown in Fig. 4-15. It can be seen that the losses in the stator copper dominate the losses in this generator system. From the results in Table 4-2, roughly 30% of the annual energy dissipation in the generator system is in the stator copper. In addition, the iron losses may be high when the wind speed is small, because the rotor frequency is relatively high during the low wind speed.

In this subsection, the DFIG_1G systems are optimized by the given different gear ratios. By comparison of the optimization results of the DFIG systems at different rated power levels, it can be seen that the single-stage gearbox cost is the main components of the generator systems cost, the highest AEP per cost may occur around 1.5MW, and the losses in the stator cooper dominate the losses in this generator system.

4.5 Evaluation of DFIG systems with different drive trains

In order to allow the convenient comparison and evaluation of the DFIG systems with the above two different drive-train types, the concerned indexes, including the generator system cost, the annual energy yield and the AEP per cost are shown in Fig. 4-16, 4-17 and 4-18, respectively. In this case, the increased or decreased percentages of the performances of the DFIG_1G system are also presented with reference to the DFIG_3G system.

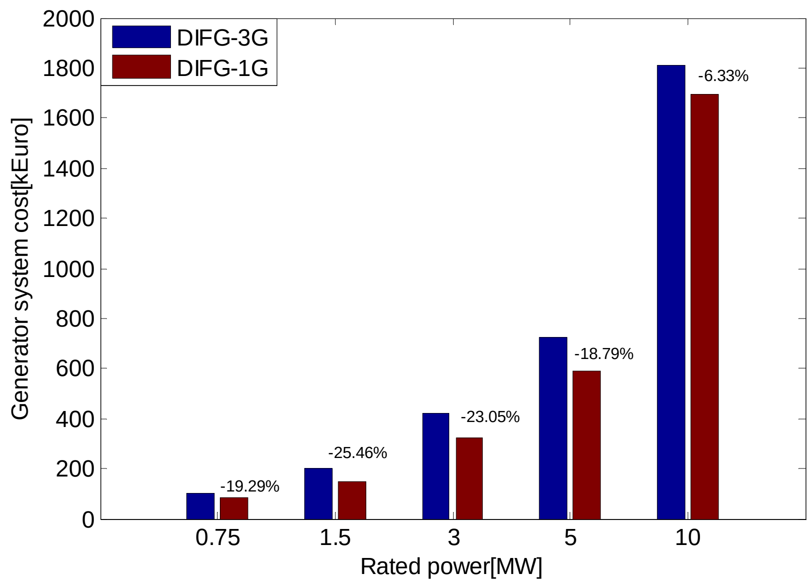


Fig.4-16：*The comparison of the generator system cost for different DFIG systems*

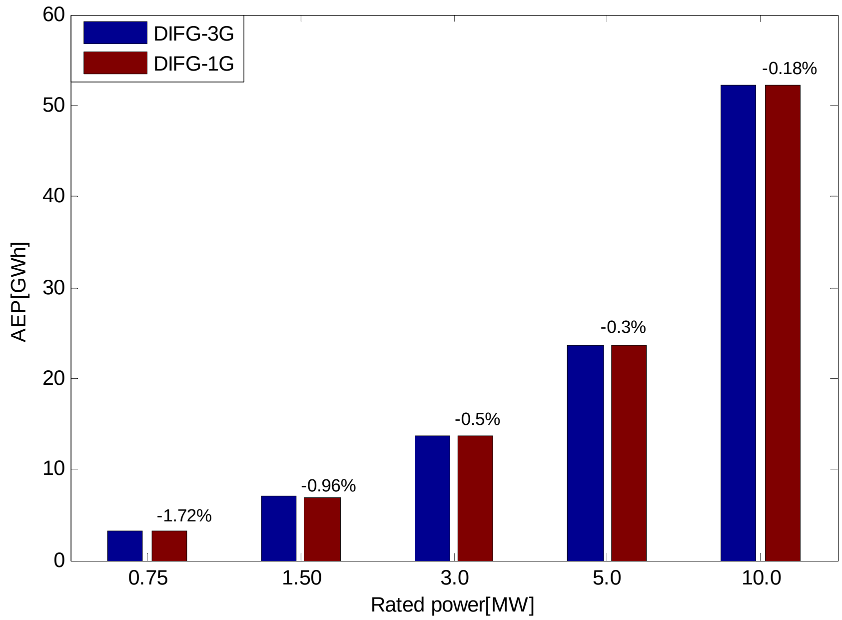


Fig.4-17：*The comparison of the annual energy yield for different DFIG systems*

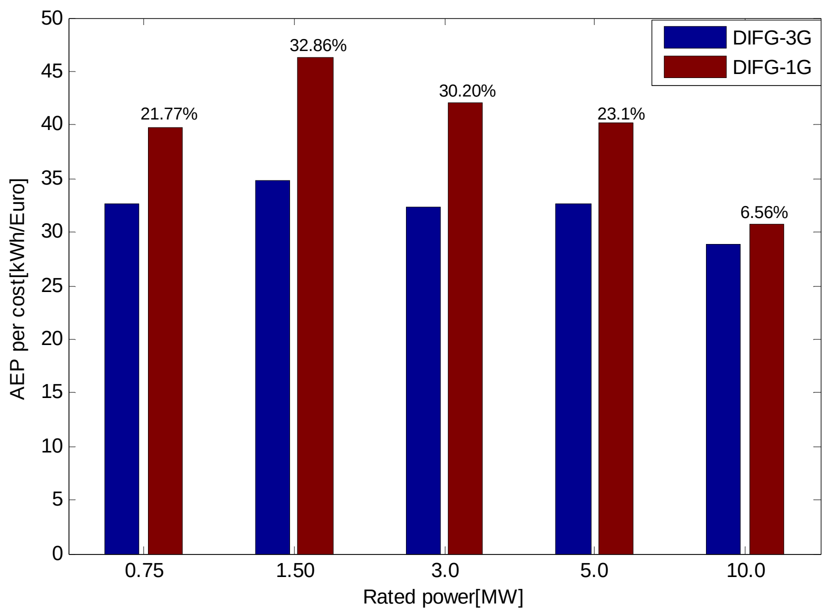


Fig.4-18：*The comparison of the AEP per cost for different DFIG systems*

It can be seen that the DFIG_1G system appears to be the cheaper alternative, and lower 20% than the DFIG_3G system. However, it may be more expensive than the DFIG_3G system when the rated power increases towards 10-MW, because the cost of the single-stage gearbox is slightly small than that of the three-stage gearbox at the rated power of 10MW. In addition, due to the lower losses in the single-stage gearbox and higher losses in the generator system, the DFIG_1G system may has a high annual energy yield as much as the DFIG_3G system. Thus, from the viewpoint of the AEP per cost, the DFIG_1G system seems the more attractive choice and has almost 20% higher than the DFIG_3G system due to the lower cost and losses in the single-stage gearbox. However, the DFIG_3G system may be more cost-effective alternative when the rated power increase towards 10-MW. Furthermore, the rated power of the most cost-effective DFIG systems may be around 1.5MW, whatever it is the DFIG_1G system or the DFIG_3G system.

4.6 Summary

In this subsection, the two drive trains with DFIG systems are investigated, including the three-stage gearbox drive train and the single-stage gearbox drive train. The basic characteristics of the different wind turbine concepts are briefly described. The optimization models and some assumptions are presented for DFIG systems. The single-stage and three-stage gearbox models are used as the same as the PMSG_1G and PMSG_3G systems, respectively. Furthermore, the design optimization of the DFIG systems with the single- and three–stage gearbox are respectively implemented, and the performances of the DFIG system, such as the cost, weight size, efficiency and AEP per cost, are compared at the different rated power levels. Finally, the optimization results of the different wind generator systems are also evaluated and analyzed. As for the two wind generator systems, the DFIG_1G system has the higher energy yield and the lower generator system cost, so that it has the higher AEP per cost. In addition, the rated power of the most cost-effective DFIG systems may be around 1.5MW, regardless of the DFIG_1G and DFIG_3G system for an average wind speed 7m/s site.

5. Design optimization of variable speed SCIG systems

The goal of this section is to investigate the most cost-effective variable speed SCIG systems with a full scale power electronic converter. The section 5 outline is as follows:

5.1 Description of the variable speed drive train concepts: This subsection introduces the advantages and disadvantages of the variable speed three-stage geared SCIG system (SCIG_3G) with a full-scale power electronic converter. The largest size from manufactures on the current market also described.

5.2 Optimization models of variable speed SCIG_3G systems: This subsection summarizes the optimized variable, the objective function and the mechanical constraints of electromagnetic design of SCIG.

5.3 Design optimization and comparison of SCIG_3G systems: This subsection summarizes the optimization results of variable speed SCIG_3G systems for designs at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The cost, weight, size, efficiency and AEP per cost of SCIG_3G are compared and analyzed, respectively.

5.4 Summary: This subsection evaluates variable speed concepts of SCIG_3G systems.

5.1 Description of the variable speed drive train concepts

For a long time, squirrel cage induction generators (SCIG) have been the most used generator types for wind turbines. The advantages of SCIG are robust technology; easy and relatively cheap mass production. The SCIG is firstly introduced as fixed speed concepts by directly connecting the grid in wind energy conversion systems. It is known as “Danish concept” [22]. This concept is very simple, robust and old concept on the market. Wind turbines of this concept were mostly manufactured during the 1980’s and 1990’s. However, this concept is not very flexible because the performance of rotor blades is optimal only at one wind speed. Therefore the efficiency of rotor blades is not constant over wide range of the wind speed. This concept also causes varying amounts of active and reactive power from the grid, resulting in flicker. In most cases, capacitors are connected in parallel to the generator to compensate for the reactive power consumption.

In order to fulfil variable speed operation with a SCIG, an alternative wind generator system is a variable speed multiple-stage geared SCIG with a full scale power electronic converter, as shown in Fig.5-1.

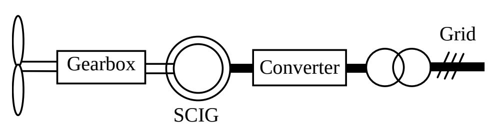


Fig. 5-1: *Scheme of a SCIG system with a three-stage gearbox (SCIG_3G)*

In this kind of the wind generator system, the electronic converter has a rectifier, a DC link and an inverter. The DC link provides a soft connection between the induction generator and the power system. The soft connection of the DC link allows the speed, voltage and frequency of the induction generator to vary with wind speed for wind gusts, maintaining a constant voltage per hertz ratio in the generator, which prevents over fluxing the generator magnetic circuit. This system has a simple, reliable generator in the nacelle along with the gearbox connecting to the turbine. The electronics could be mounted in the nacelle or in the base of the tower. The system should be quite reliable, with reliability hinging on that of the power electronics. In addition, this system can run at unity power factor, leading or lagging power factor.

Compared with “Danish concept”, this concept has advantages of the flexible control with a full-scale power, such as variable speed operation at all wind speeds, better performances of reactive power compensation and smooth grid connection. However, its disadvantage is the high cost and losses of the full-scale converter, the efficiency of the total system (gearbox induction generator and converter) may be low [27]. Currently, Siemens is using this concept in the model of Bonus 107-3.6 MW on the market (see Fig.5-2) [27].

Fig. 5-2: *Siemens SWT-3.6-107 (SCIG_3G)*

5.2 Optimization models of SCIG_3G systems

The analytical design models of SCIG have been presented in section 4 of report 1. In this subsection, the optimization models of the variable speed SCIG_3G system are introduced.

1. Objective function

In order to obtain the most cost-effective SCIG_3G system, the proposed criterion includes the generator system cost

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} + C_{gear} \quad (5\text{-}1)$$

where C_{gear} three-stage gearbox cost; the meanings of other variables can be seen in the equation (3-1).

As the basis for this criterion, the different specific component costs are given in Table 1-3, respectively.

2. Optimized variables

In order to optimize the machines to the criterion (5-1), six variables are chosen to vary within a certain range, including the air gap radius (r_s), the stator length (L), the slot height (h_s), the pole pitch (τ_p), the peak air gap flux density ($\hat{B}_{g0}$) and the peak stator yoke flux density ($\hat{B}_{ys}$). The variable of r_s is chosen as the same value of PMSG_3G system.

3. Assumptions and constraints

The following assumptions are used in the optimization program:

•The number of slots per pole per phase is assumed to be 6 in order to reduce the additional losses in the SCIG.

•The rated slip is fixed to -0.002 at the different rated power levels of SCIG systems in order to reduce the rotor copper losses and improve the generator efficiency.

•The air gap radius is fixed to be the same value of the PMSG_3G system, in order to compare with the different wind generator systems with the same three-stage geared drive train.

•A two-layer winding with two conductors per slot ($N_{slot} = 2$) is used to make the end windings simple due to an integer slot winding.

•The stator slots are open and a non-magnetic wedge thickness is $h_w = 5$ mm.

•The stator is set to a constant value, i.e. it is 0.65 for the stator outer diameters larger than 2m; below 2m, it is assumed to be 0.4.

•The slot width is assumed to be 45% of the slot pitch and the stator slots are skewed by one slot pitch.

•For mechanical reasons, the ratio of slot depth to slot width is limited within the range of 4-10, which prevents excessive tooth mechanical vibrations from occurring [20].

•The air gap is fixed to 1mm in order to improve the power factor.

•The current density in the stator windings is limited to 3-6 A/mm^2, and the current loading is limited to 40-60 kA/m to prevent excessive and avoid critical cooling requirements.

5.3 Design optimization and comparison of SCIG_3G systems

In order to investigate the performances of the multi-stage geared drive SCIG systems over a range of power ratings, the mentioned optimization models are used to optimize the SCIG_3G systems for designs at 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW. The models of the three-stage gearbox are used as the same as the PMSG_3G system, which have been presented in subsection 2.5.1. The cost, weight, size, efficiency and AEP per cost are compared graphically as the following, respectively.

1. Generator system cost

Fig. 5-3 depicts the generator system cost function for each optimization design. In order to see the component cost at different rated powers, the cost of the generator active material, the generator structure, the three-stage gearbox, and the power electronic converter are also shown in Fig. 5-3.

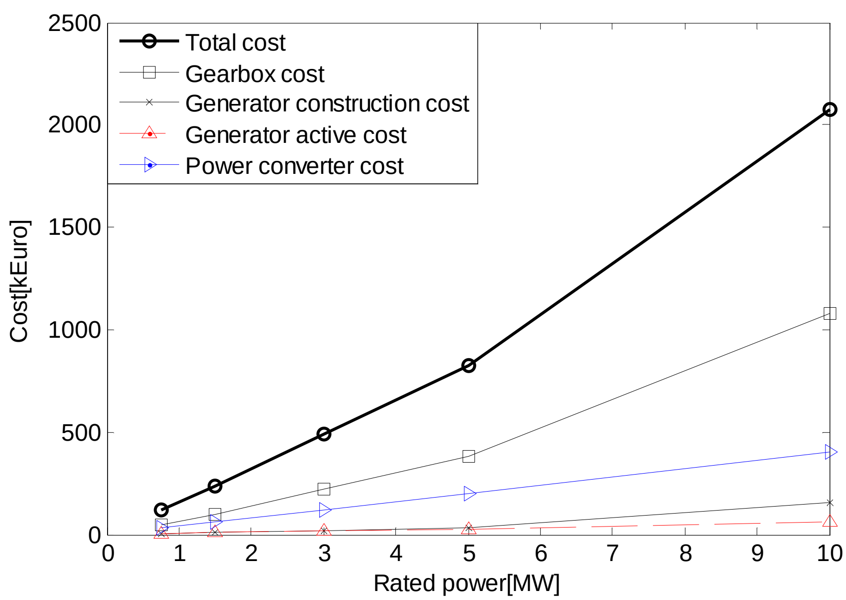


Fig.5-3： *The variable speed SCIG_3G system cost as a function of rated power*

The results show that the three-stage gearbox cost and the power electronic cost are the main components of the generator system cost. The cost of the power electronic converter is also high due to the full-scale rated power of this generator system. The cost of the generator active materials and the generator structure are very low, due to the high rotor speed. It can be seen that the generator system cost increase quickly when the rated power increases towards 10MW, because the high torque of the low-speed shaft leads to the rapid increase for the cost of the three-stage gearbox.

2. Generator system weight

The generator system weight including the active material part and the three-stage gearbox are shown in Fig. 5-4. It can be seen that the three-stage gearbox is the main component of the generator system weight. The three-stage gearbox weight may increase rapidly for 10-MW SCIG_3G system, due to the larger shaft torque of the gearbox.

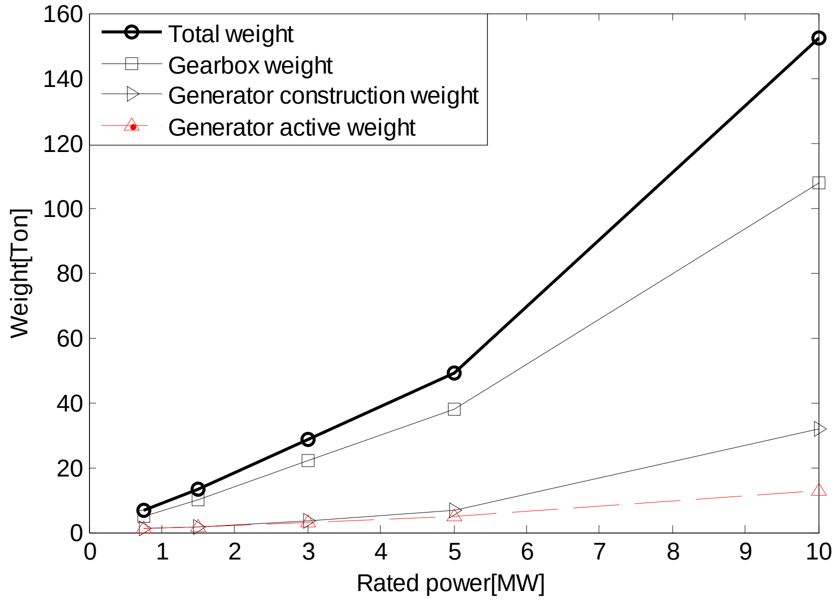


Fig.5-4：*The weight of the SCIG_3G system as a function of the rated power*

3. Generator size

The estimated outer diameter of the stator and the approximate total length of the stator, including the end windings, are plotted as a function of the rated power in Fig. 5-5.

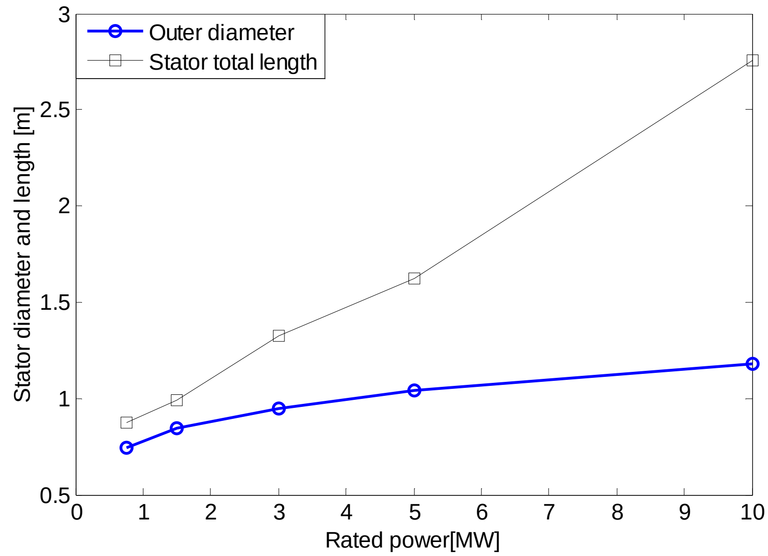


Fig.5-5：*The outer diameter and stator total length as a function of the rated power*

It can be seen that the outer diameter and the length increases with increasing rated power, but the increase of the outer diameter is rather small. For example, as for the large SCIG system of 10-MW, the stator outer diameter may be only about 1.5m, and the stator total length is about 1.8m.

4. Full load efficiency

Both the generator efficiency and the system efficiency including the loss in the three-stage gearbox and the power electronic converter at rated load of the optimized SCIG_3G systems are shown in Fig. 5-6. Because the rated rotor speed is at 1200rpm, the generator efficiency is high. Due to the losses in the three-stage gearbox and the full-scale power electronic converter, the system efficiency at rated load is about 6 percent lower than the generator efficiency.

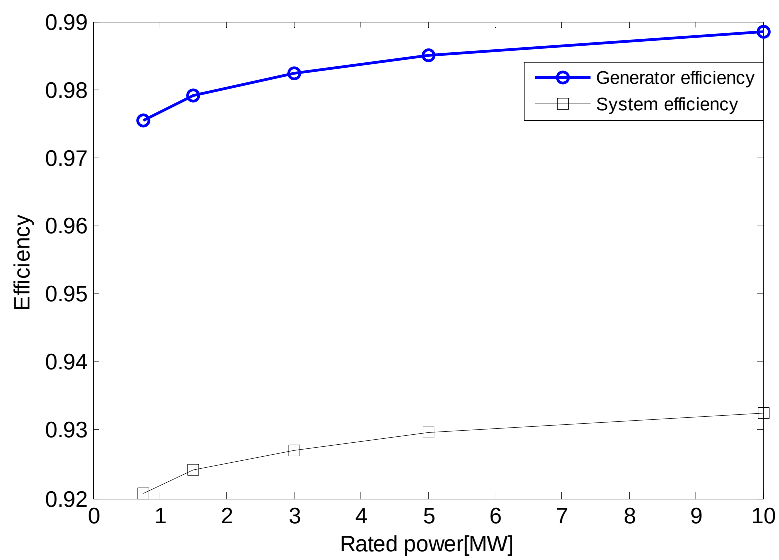


Fig.5-6：*The efficiency at full load as a function of rated power*

5. AEP per cost

The annual energy production is also calculated according to the annual average wind speed at the hub height for each design. Fig. 5-7 depicts the AEP per cost as a function of the rated power.

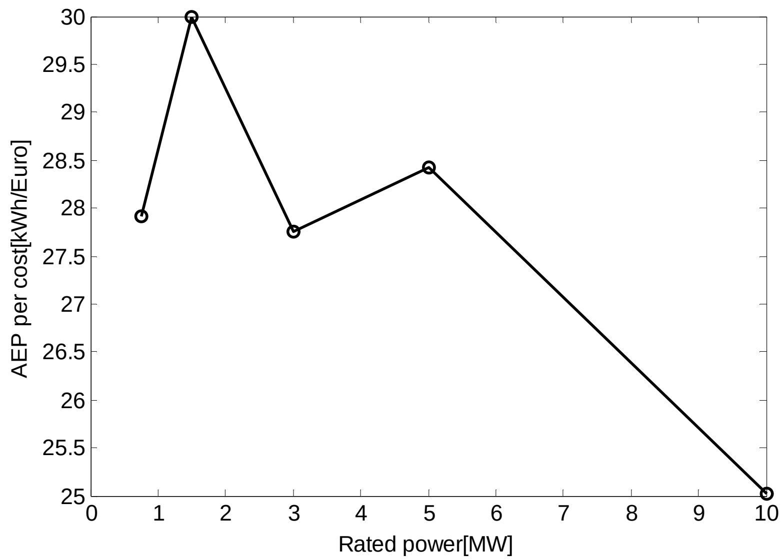


Fig.5-7：*The AEP per cost as a function of rated power*

The results shown the rated power of the most cost-effective variable speed SCIG_3G systems may be around 1.5MW, when the rated power is larger than 1.5MW, the AEP per cost decreases as the power ratings increase, but the decrease is rather small.

As a design reference of the SCIG_3G system, Table 5-1 summarizes the system important dimensions and performances resulting from each optimal design.

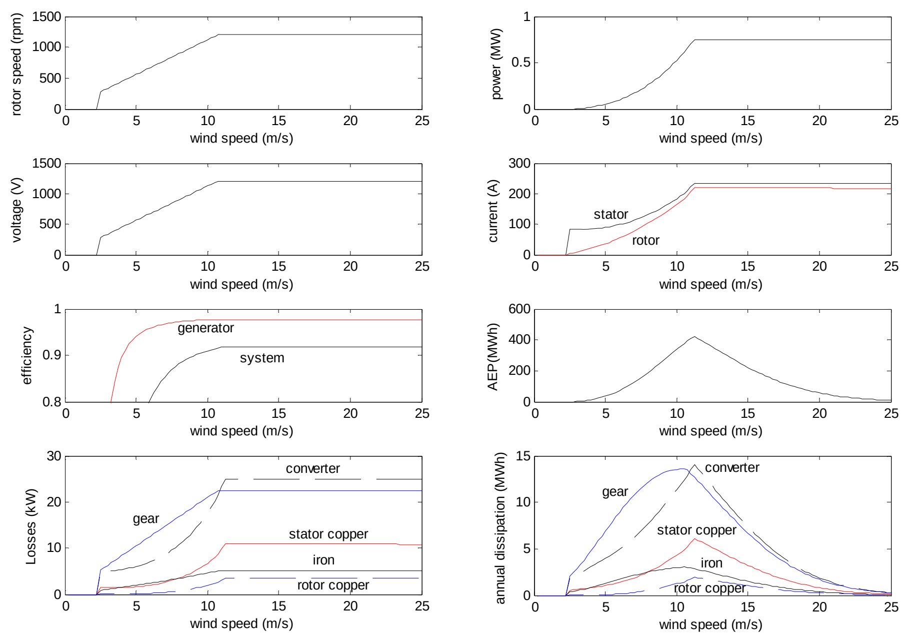
Table 5-1: *Main Performances of the optimized SCIG_3G systems*

Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
Wind turbine					
Rotor diameter *D* [m]	50	70	90	115	170
Rated wind speed v_N [m/s]	11.2	11.3	12.0	12.1	11.7
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Given gear ratio	41.96	58.54	75.00	81.1	120.0
SCIG system dimensions and electrical performances					
Generator rated rotor speed [rpm]	1200	1200	1200	1200	1200
Air gap diameter D_{i1} [m]	0.58	0.68	0.76	0.84	0.86
Stator length *L* [m]	0.51	0.62	0.91	1.18	2.0
Pole pitch *Tp* [mm]	185	184	208	221	387
Stator slot height h_s [mm]	40.5	46.7	48.5	51.8	67.9
Stator slot width b_s [mm]	5.5	5.5	6.3	6.4	9.9

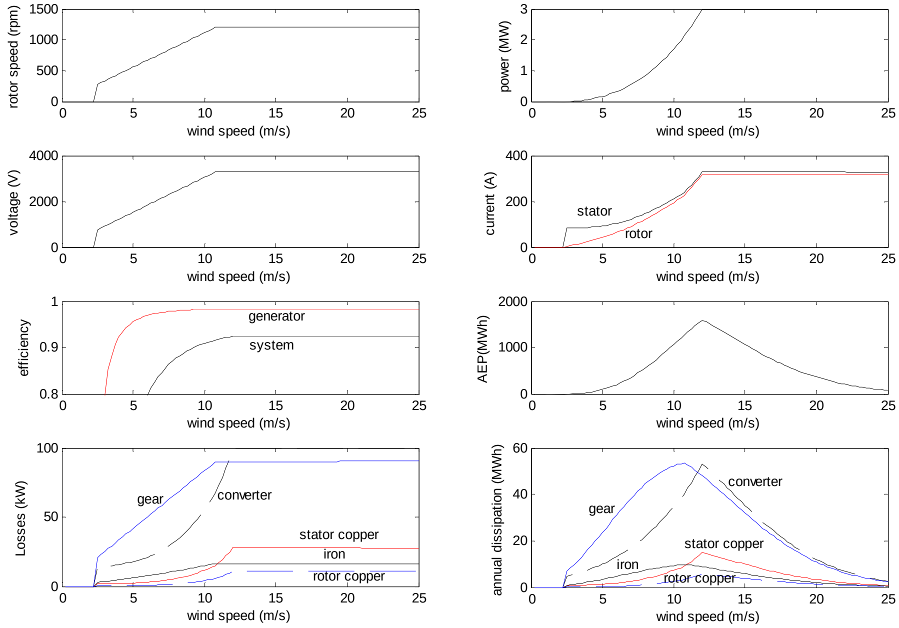
Stator tooth width b_{sd} [mm]	4.8	4.7	5.3	5.9	11.6
Stator yoke height h_{ys} [mm]	39.7	37.5	43.4	49.8	92.6
Rotor yoke height h_{yr} [mm]	39.7	37.5	43.4	49.8	92.6
Rotor slot height h_r [mm]	40.5	46.7	48.5	51.8	67.9
Rotor slot width b_r [mm]	3.9	3.8	4.3	4.8	9.5
Rotor tooth width b_{rd} [mm]	4.8	4.7	5.3	5.9	11.6
Peak air gap flux density B_{g0} [T]	0.81	0.76	0.78	0.83	0.90
Peak stator yoke flux density B_{ysm} [T]	1.20	1.19	1.20	1.17	1.19
Number of pole pairs N_p	5	6	6	6	3
Generator output frequency [Hz]	99.8	119.8	119.8	119.8	59.9
Generator output phase voltage [V]	1206	1966	3293	5016	4663
Generator output phase current [A]	233	277	328	359	749
Stator resistance [pu]	0.0129	0.0107	0.0086	0.0069	0.0063
Stator leakage inductance [pu]	0.0427	0.0475	0.0434	0.0405	0.0624
Excited magnetic inductance [pu]	1.3781	1.5802	1.6152	1.5997	6.0509
Rotor resistance [pu]	0.0043	0.0039	0.0034	0.0026	0.002
Rotor leakage inductance [pu]	0.0503	0.0598	0.0558	0.0492	0.0592
Current density [A/mm^2]	6	6	6	6	6
Full load generator efficiency [%]	97.6	97.9	98.2	98.5	98.8
Full load system efficiency [%]	92.1	92.4	92.7	93.0	93.3
Generator material weight [Ton]					
Iron	0.87	1.27	2.29	3.74	11.06
Stator copper	0.11	0.17	0.27	0.37	0.65
Rotor copper	0.15	0.25	0.40	0.60	1.28
Active material	**1.13**	**1.69**	**2.96**	**4.71**	**1.30**
Construction	**1.08**	**1.57**	**3.66**	**6.66**	**31.71**
Gearbox	**4.75**	**9.77**	**21.88**	**37.85**	**107.66**
Total weight	**6.96**	**13.03**	**28.50**	**49.22**	**15.24**
Component cost [kEuro]					
Generator active material	6.4	10.1	17.0	25.7	62.2
Generator construction	5.4	7.9	18.3	33.28	158.5
Three-stage gearbox	47.5	97.7	218.8	378.5	1076.6
Power electronic converter	30	60	120	200	400

Electrical subsystem	28.5	57	114	190	380
Generator system cost	**117.9**	**232.6**	**488**	**827.6**	**2077.3**
Cost per kilowatt [Euro/kW]	**157**	**155**	**163**	**166**	**208**
Annual energy					
Stator copper loss [MWh]	49	78	118	178	343
Rotor copper loss [MWh]	13	26	43	63	107
Iron loss [MWh]	30	55	103	155	208
Converter loss [MWh]	124	249	484	850	1807
Gearbox loss [MWh]	142	292	593	923	1906
Total loss [MWh]	359	700	1340	2171	4371
AEP [GWh]	3.29	6.98	13.54	23.52	51.98
AEP per cost[kWh/Euro]	27.92	30	27.76	28.42	25.02

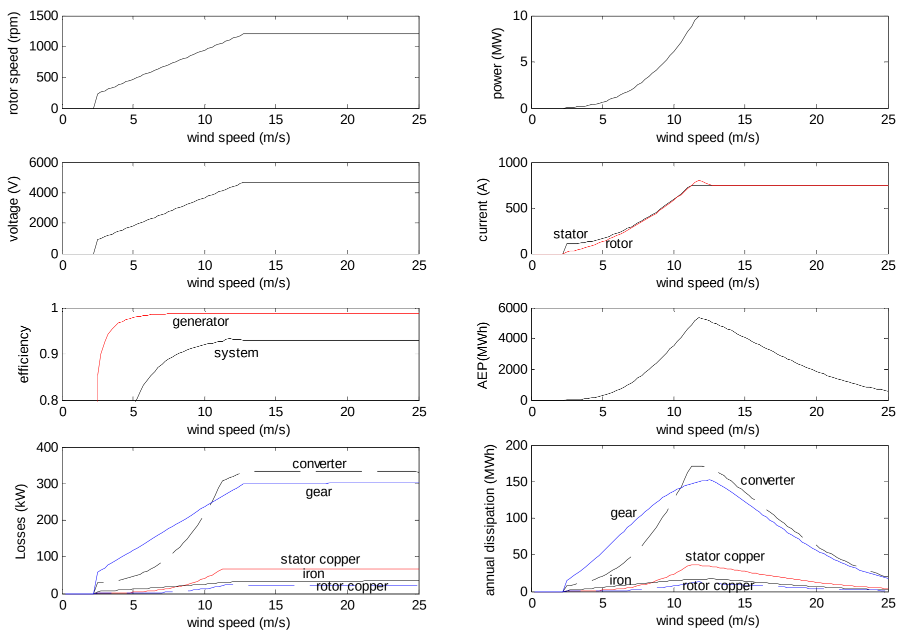
In order to further show the operational performances of the optimized SCIG_3G systems, as for examples of small, middle and large variable speed SCIG_3G systems, Fig. 5-8 (a-c) depict some characteristics of 0.75-MW, 3.0-MW and 10.0-MW SCIG_3G systems as a function of the wind speed: generator rotor speed, stator voltage, stator and rotor currents, grid power, efficiency and losses in the generator system.



(a) 0.75-MW SCIG_3G



(b) 3.0-MW SCIG_3G



(c) 10.0-MW SCIG_3G

Fig.5-8：*The characteristics of the SCIG_3G system as a function of the wind speed for 0.75-MW, 3.0-MW and 10.0-MW rated power*

The AEP and the annual energy dissipation are also shown in Fig. 5-8. It can be seen that the largest part of the losses is losses in the three-stage gearbox, which is almost over 43% of the annual dissipation in this generator system. In addition, the losses in the power converter are also high and over 35% of the annual dissipation in the generator system.

5.4 Summary

In this section, the variable speed three-stage geared drive SCIG system with a full-scale power electronic converter is investigated. Firstly, the basic description of this generator system is introduced. Then the optimization models and some assumptions are presented. The optimization designs have been implemented at the rated power of 0.75-MW, 1.5-MW, 3-MW, 5-MW and 10-MW, respectively. Finally, the optimization results of the variable speed SCIG_3G systems at the different rated power levels are evaluated and analyzed. From the above comparison and analysis, it can be seen that the generator efficiency is relatively high due to the high generator rotor speed and variable speed operation. The cost of the three-stage gearbox and the power electronic converter are main parts of this generator system cost. From the viewpoint of the AEP per cost, the rated power of the most cost-effective SCIG_3G system is around 1.5MW. In addition, the losses in the three-stage gearbox and the power electronic converter dominate the losses in this generator system, and the energy dissipation in the generator is very small for this concept.

6. Evaluation of different wind generator systems

The goal of this section is to evaluate and summarize the results presented in sections 2 through 5 to allow a convenient comparison. The used criteria include the costs of the generator system components, the generator system weight, the annual energy yield and the AEP per cost. Firstly, according to the classification of wind turbine drive-train types, the performances are evaluated for the different wind generator systems. Next, as examples of small, middle, large rated powers of wind generator systems, the performances of all investigated wind generator systems are compared for each rated power, so that the most cost-effective wind generator systems are further evaluated. The section 6 outline is as follows:

6.1 Evaluation of direct-drive wind generator systems: This subsection summarizes the results and comparisons of the optimized PMSG_DD and EESG_DD systems in terms of the cost, weight, annual energy yield and AEP per cost.

6.2 Evaluation of the single-stage geared drive wind generator systems: This subsection summarizes the results and comparisons of the optimized PMSG_1G and DFIG_1G systems in terms of the cost, weight, annual energy yield and AEP per cost.

6.3 Evaluation of the three-stage geared drive wind generator systems: This subsection summarizes the results and comparisons of the optimized PMSG_3G, DFIG_3G and SCIG_3G systems in terms of the cost, weight, annual energy yield and AEP per cost.

6.4 Evaluation of the investigated wind generator systems: This subsection summarizes the results and comparisons of all investigated wind generator systems, including PMSG_DD, PMSG_1G, PMSG_3G, EESG_DD, DFIG_3G, DFIG_1G and SCIG_3G systems at the rated power of 0.75-MW, 3.0MW and 10.0-MW, respectively.

6.1 Evaluation of direct-drive wind generator systems

In order to investigate the performances of direct-drive wind generator systems, the generator system cost, the generator system weight, the annual energy yield and AEP per cost of the PMSG_DD and EESG_DD systems are compared graphically as the following, respectively. In this case, the increased or decreased percentages of the performances of the PMSG_DD system are presented with reference to the EESG_DD system.

1. Generator system cost

Fig.6-1 shows the generator system cost of direct-drive PMSG and EESG systems for each optimization design and their comparisons. It can be seen that the PMSG_DD system is slightly cheaper than the EESG_DD system due to the lower PM generator active material cost. The generator system cost of the PMSG_DD system could reduce over 12% on average in comparison with the EESG_DD system, the reduced percentage may improve as wind turbine sizes increase.

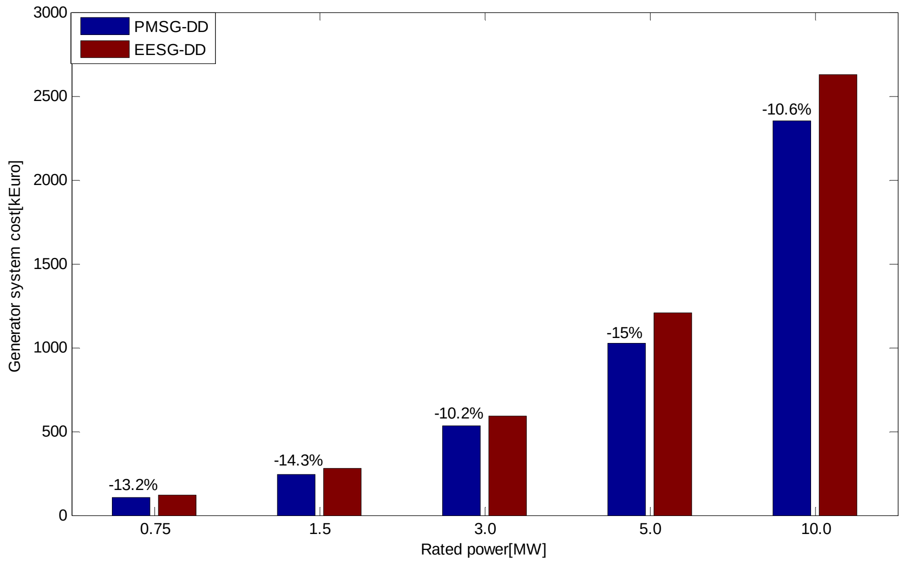


Fig. 6-1: *The generator system cost of direct-drive different generator systems*

2. Generator system weight

Fig.6-2 shows the weight of the active material of direct-drive PMSG and EESG systems for each rated power level. It can be seen that the PMSG_DD system is lighter than the EESG_DD system, because the weight of the iron and copper in EESG is higher. With the rated power increases, the advantage of the PMSG_DD appears more and more obvious in terms of generator material weight. For example, at the rated power of 5-MW and 10-MW, the weight of the PMSG_DD system is nearly halved in comparison with the EESG_DD system.

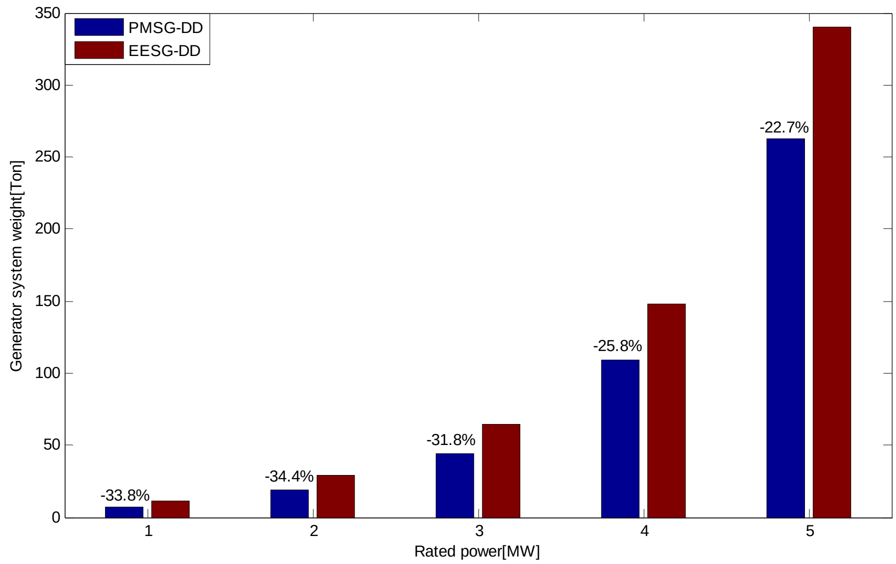


Fig. 6-2: *The weight of direct-drive different generator systems*

3. Annual energy yield

Fig.6-3 depicts the annual energy yield of direct-drive PMSG and EESG systems for each rated power level. The comparison shows that the PMSG_DD system has 3% higher energy yield than the EESG_DD system, because the EESG has the additional rotor copper losses.

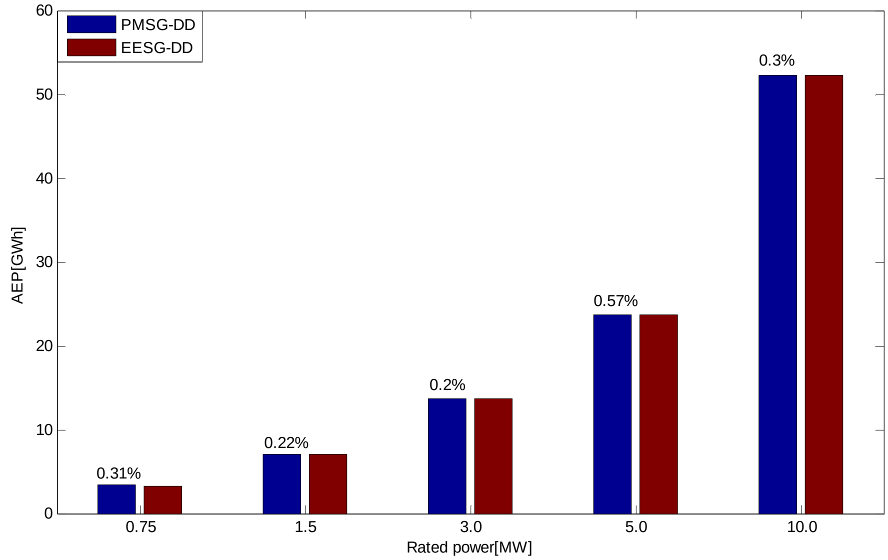


Fig. 6-3: *The annual energy yield of direct-drive different generator systems*

4. AEP per cost

Fig.6-4 depicts the AEP per cost of direct-drive PMSG and EESG systems for each rated power level. It can be seen that the direct-drive wind generator systems have a slightly decrease in the AEP per cost as the rated power increases, regardless of the EESG_DD and PMSG_DD system. This is because the generator structural cost could rise more rapidly than the increase of the annual energy yield. In addition, the PMSG_DD system has higher AEP per cost than the EESG_DD system, and it has nearly an average 15% improvement.

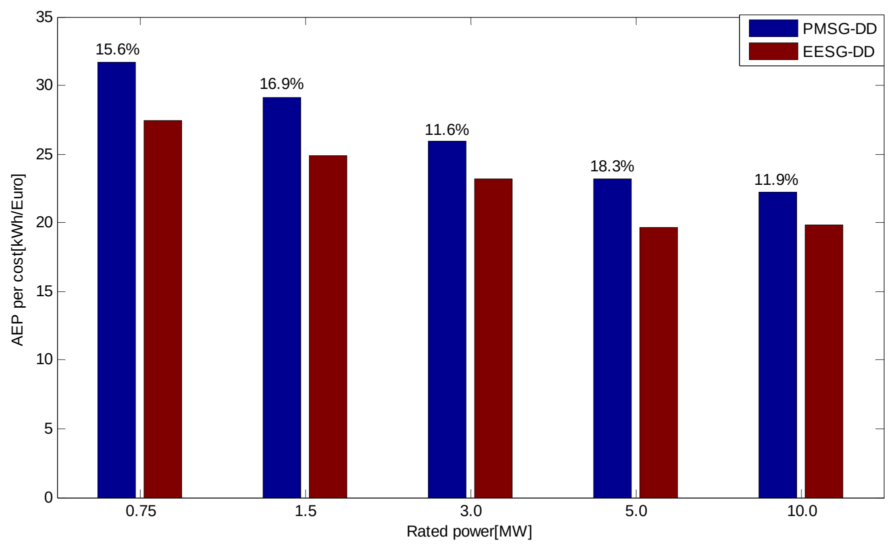


Fig. 6-4: *The AEP per cost of direct-drive different generator systems*

From the above comparisons of the direct-drive different wind generator systems, the PMSG_DD system could be more cost-effective choice, because it has lower active material weight, the cheaper generator system cost, the higher energy yield and the higher AEP per cost. In addition, from the viewpoint of the AEP per cost, the direct-drive wind generator system with small rated power may be more attractive. However, compared with the EESG_DD system, the advantage of the PMSG_DD system with the larger rated power level may be more obvious.

6.2 Evaluation of the single-stage geared drive wind generator systems

In order to investigate the performances of wind generator systems with the single-stage gearbox, the generator system cost, the generator system weight, annual energy yield and the AEP per cost of the PMSG_1G and DFIG_1G systems are compared graphically as the following, respectively. In this case, the increased or decreased percentages of the performances of the PMSG_1G system are presented with reference to the DFIG_1G system.

1. Generator system cost

Fig.6-5 shows the generator system cost of the PMSG_1G and DFIG_1G systems for each optimal design. It can be seen that the PMSG_1G system is more expensive than the DFIG_1G system, for a MW wind generator system, the PMSG_1G system could increase over 14% of the generator system cost system. This is because the cost of the power electronic converter for the PMSG_1G system is higher than that of the DFIG_1G system.

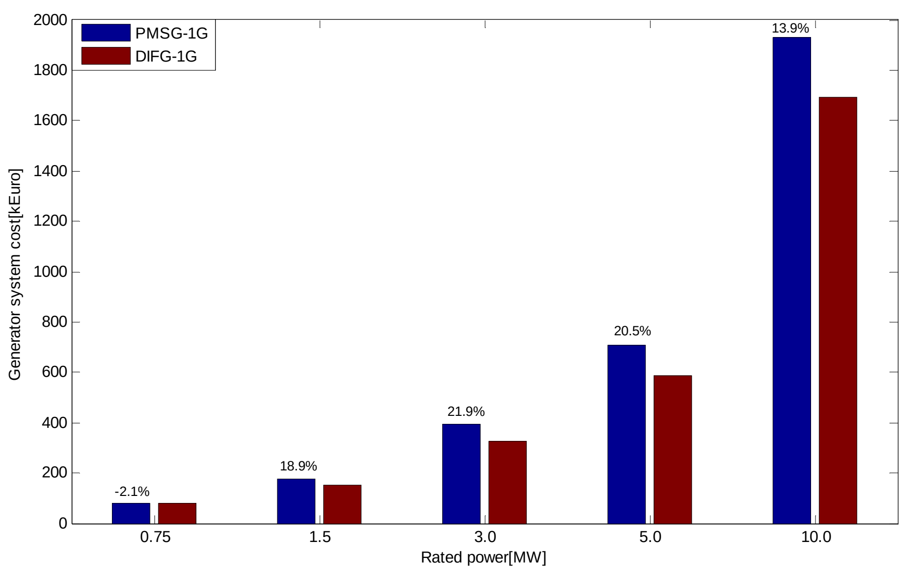


Fig. 6-5: *The system cost of different generator systems with the single-stage gearbox*

2. Generator system weight

Fig.6-6 shows the generator system weight of the PMSG_1G and DFIG_1G systems for each optimal design. It can be seen that the PMSG_1G system is slightly lighter than the DFIG_1G system due to having less iron materials in PM generator. Compared with the DFIG_1G system, the reduced percentage of the PMSG_1G appears more and more obvious as the rated power decreases. For example, at the rated power of 10-MW, the weight of the PMSG_1G system is only reduced at 5.7%, whereas for the 0.75MW, it is nearly 56%.

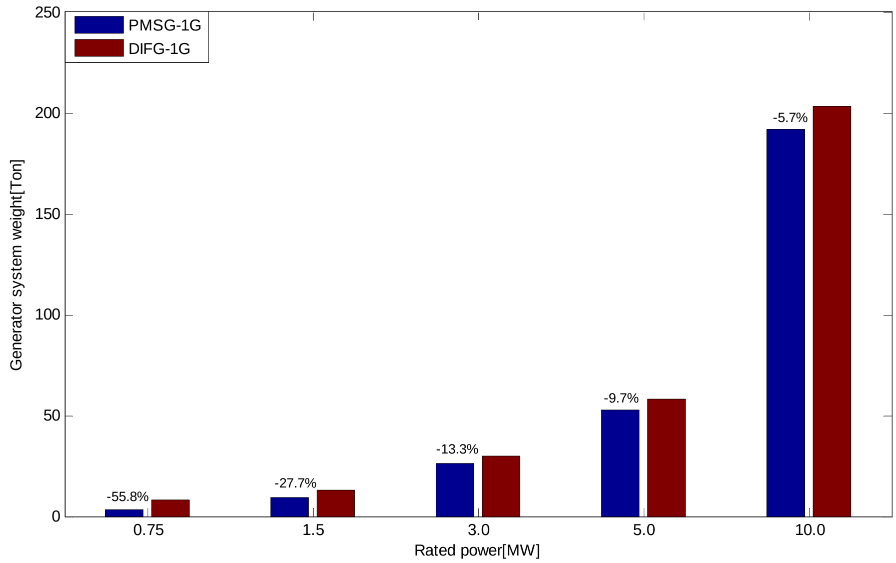


Fig. 6-6: *The weight of different generator systems with the single-stage gearbox*

3. Annual energy yield

Fig.6-7 depicts the annual energy yield of the PMSG_1G and DFIG_1G systems for each optimization design. The comparison shows that the PMSG_1G system has 1% higher energy yield than the DFIG_1G system due to the higher PM generator efficiency, and the increment of the energy yield for the PMSG_1G may reduce with the rated power increase.

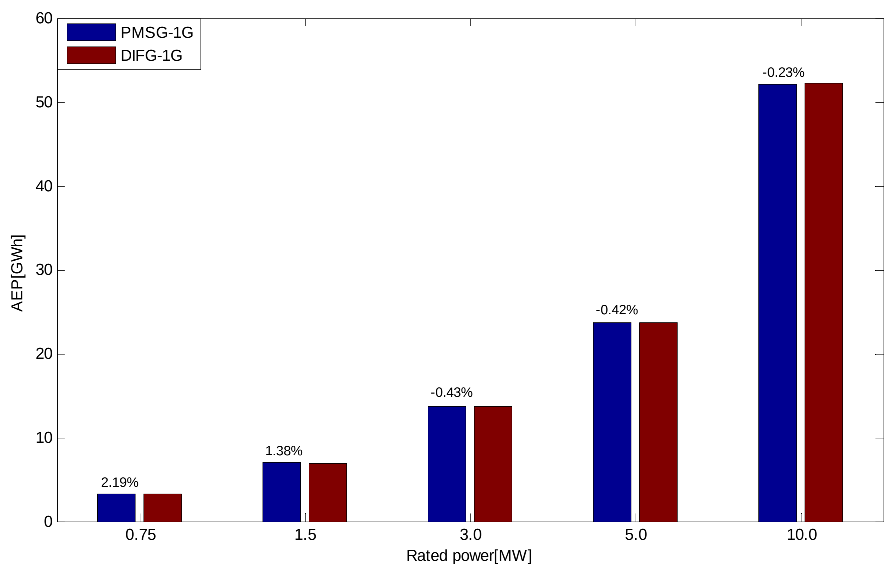


Fig. 6-7: *The annual energy yield of different generator systems with the single-stage gearbox*

4. AEP per cost

Fig.6-8 depicts the AEP per cost of the PMSG_1G and DFIG_1G systems for each optimal design. It can be seen the PMSG_1G system have a lower AEP per cost than the DFIG_1G system, especially for MW levels, the reduced percentage is around 15%. In addition, for the DFIG_1G system, the power range with high AEP per cost is from 1.5MW to 5MW.

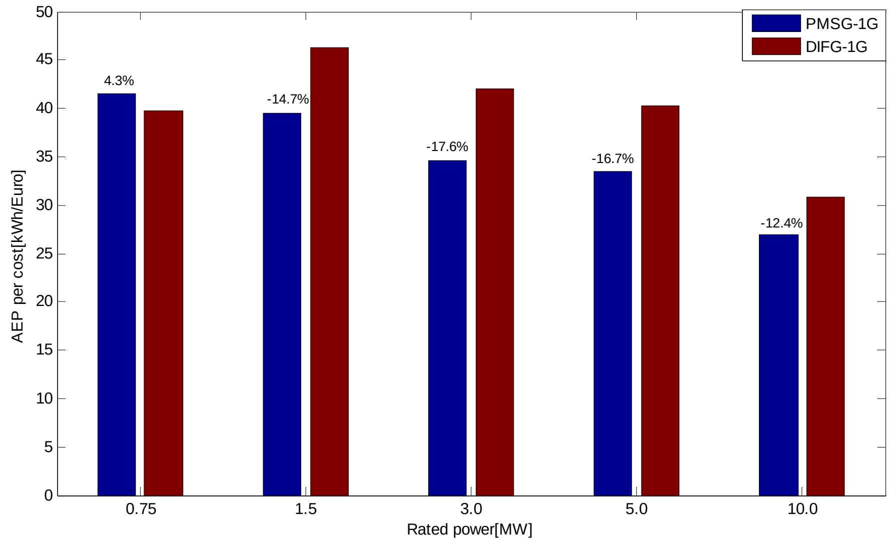


Fig. 6-8: *The AEP per cost of different generator systems with the single-stage gearbox*

From the above evaluation of the different wind generator systems with a single-stage gearbox, it can be seen that the DFIG_1G system seems to be more attractive choice, because it has the lower generator system cost, the higher energy yield and the higher AEP per cost, even though it has a slightly heavier in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the most cost-effective DFIG_1G system may occur around 1.5MW. The DFIG_1G system will keep a higher level in the AEP per cost from 1.5-MW to 5-MW.

6.3 Evaluation of the three-stage geared drive wind generator systems

In order to investigate the performances of wind generator systems with the three-stage gearbox, the generator system cost, the generator system weight, annual energy yield and the AEP per cost of the PMSG_3G, SCIG_3G and DFIG_3G systems are compared graphically as the following, respectively. In this case, the increased or decreased percentages of the performances of the PMSG_3G and SCIG_3G systems are presented in comparison with the DFIG_3G system.

1. *Generator system cost*

Fig.6-9 shows the generator system costs of the PMSG_3G, SCIG_3G and DFIG_3G systems for each optimal design. It can be seen that the DFIG_3G system is the lowest cost solution due to the partial-scale power electronic converter. In addition, the PMSG_3G system is slightly cheaper than the SCIG_3G system, due to the lower outer diameter and stator total length of high speed PM machine, so that the generator structural cost of the PMSG_3G system is lower. It is mentioned that the unit generator structural cost is chosen as the same value in this study, regardless of synchronous generator and induction generators. Compared with the DFIG_3G system, the cost of the SCIG_3G system could increase over 13%, whereas for the PMSG_3G system, it is almost around 10%.

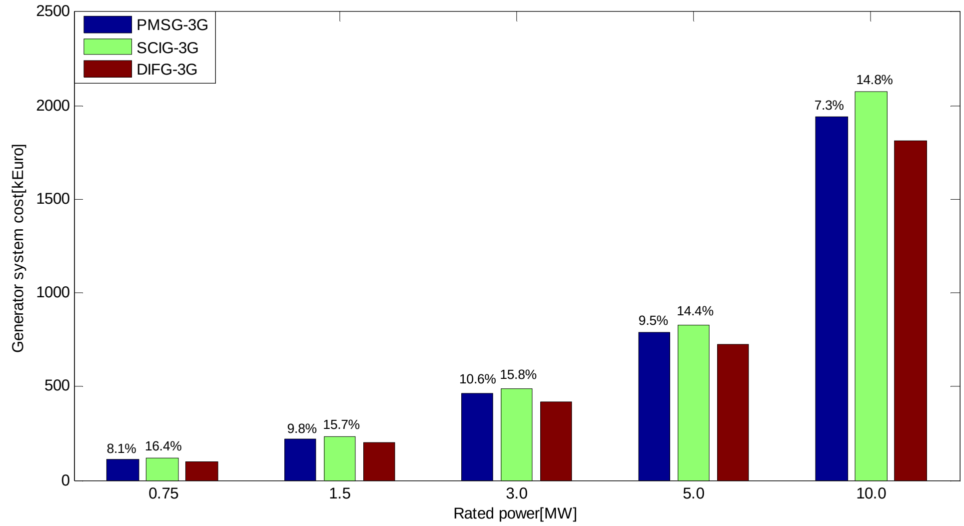


Fig. 6-9: *The system cost of different generator systems with the three-stage gearbox*

2. Generator system weight

Fig.6-10 shows the generator system weight of the PMSG_3G, SCIG_3G and DFIG_3G systems for each optimal design. It can be seen that the DFIG_3G system is the heaviest due to having more iron materials in DFIG. The PMSG_3G system is slightly lighter than the SCIG_3G system. Compared with the DFIG_3G system, the weight of the PMSG_3G system is nearly reduced around 20%, whereas for the SCIG_3G system, it is nearly around 13%.

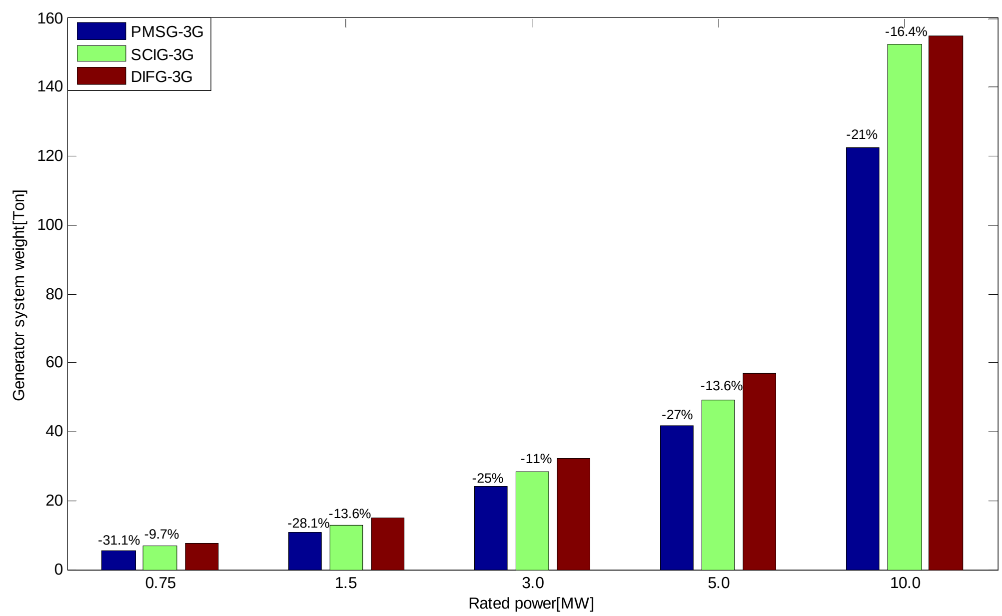


Fig. 6-10: *The weight of different generator systems with the three-stage gearbox*

3. Annual energy yield

Fig.6-11 depicts the annual energy yield of the PMSG_3G, SCIG_3G and DFIG_3G systems for each optimization design. The comparison shows that the DFIG_3G system has the highest energy yield due its lowest losses in the converter, whereas the SCIG_3G system has slightly higher energy yield than the PMSG_3G system, due to a lower iron losses in SCIG. Compared with the DFIG_3G system, the reduced percentage of the SCIG_3G system is nearly around 0.5%, whereas for the PMSG_3G system, it is nearly around 1%.

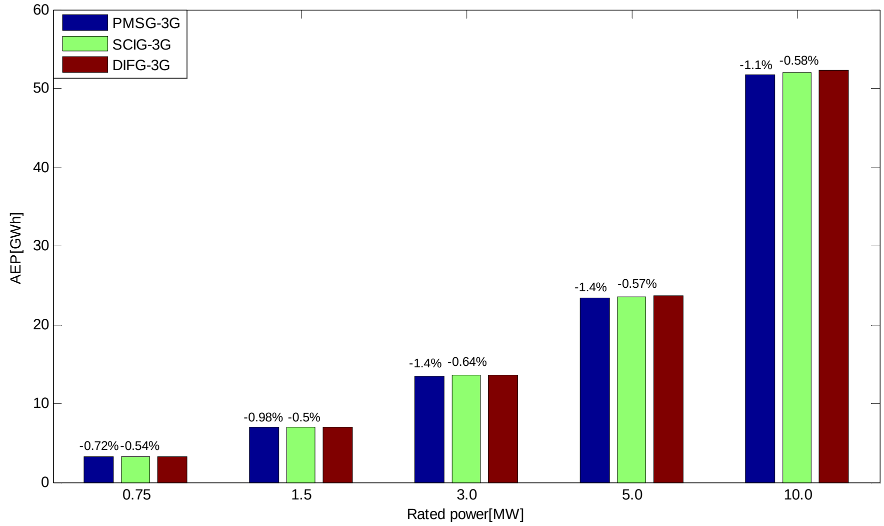


Fig. 6-11: *The annual energy yield of different generator systems with the three-stage gearbox*

4. AEP per cost

Fig.6-12 depicts the AEP per cost of the PMSG_3G, SCIG_3G and DFIG_3G systems for each optimal design. It can be seen the DFIG_3G system has the highest AEP per cost, whereas the PMSG_3G system is higher than the SCIG_3G system. Compared with the DFIG_3G system, the PMSG_3G system could reduce over 8%, whereas for the SCIG_3G system may decrease nearly around 13%. In addition, it can be seen that the power level of the most cost-effective wind generator system with the three-stage gearbox is around 1.5-MW, regardless of the PMSG_3G, SCIG_3G and DFIG_3G systems.

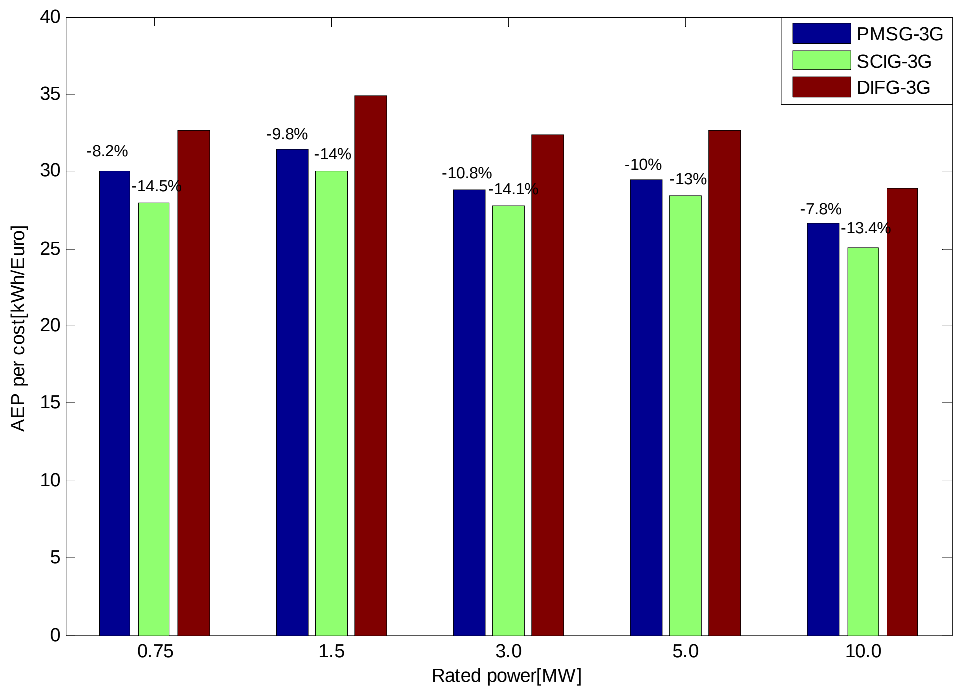


Fig. 6-12: *The AEP per cost of different generator systems with the three-stage gearbox*

From the above comparisons of the different wind generator systems with a three-stage gearbox, it can be seen that the DFIG_3G system seems to be the most attractive choice, because it has the lower generator system cost, the higher energy yield and the higher AEP per cost, even though it is slightly heavier in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the PMSG_3G system is more interesting than the SCIG_3G system. Furthermore, the most cost-effective wind generator system with the three-stage gearbox may occur around the rated power of 1.5MW.

6.4 Evaluation of the investigated wind generator systems

In order to further evaluate the performances of different wind generator systems, the generator system cost, the generator system weight, annual energy yield and the AEP per cost of the investigated wind generator systems are compared graphically as the following, respectively. As examples of small, middle, large rated powers of wind generator systems, in this case, the comparisons are focused on the rated power of 0.75-MW, 3.0-MW and 10-MW.

1. Generator system cost

Fig.6-13 shows the generator system cost of the different wind generator systems. It can be seen that the single-stage geared wind generator system is the lowest cost solution at small and medium rated powers; however, the DFIG_1G system may be the cheapest when the rated power increases towards 10MW. In addition, the direct-drive wind generator system is the most expensive choice.

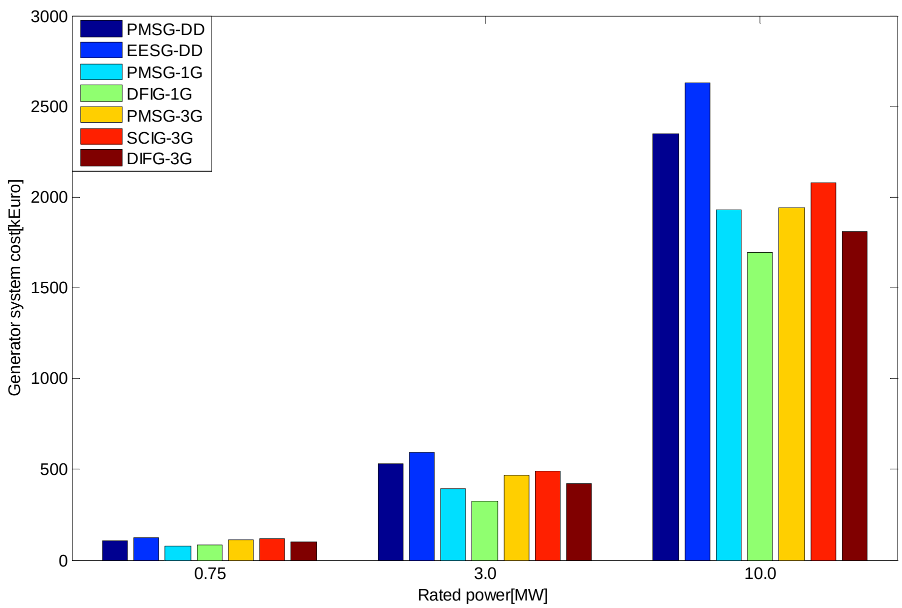


Fig. 6-13: *The system cost of different wind generator systems*

2. Generator active weight

Fig.6-14 shows the generator system weight of the investigated different wind generator systems. It can be seen that the wind generator systems with a single-stage gearbox are the heaviest at 10-MW wind turbine size. Therefore, this wind turbine concept may be suitable to apply for small and medium turbine sizes. Though the weight of the direct-drive wind generator system seems more attractive, it is noted that only generator active materials weight is considered here in direct-drive wind turbine concepts. As generally, the weight of the direct-drive generator structure is expected to be much higher than its active weight.

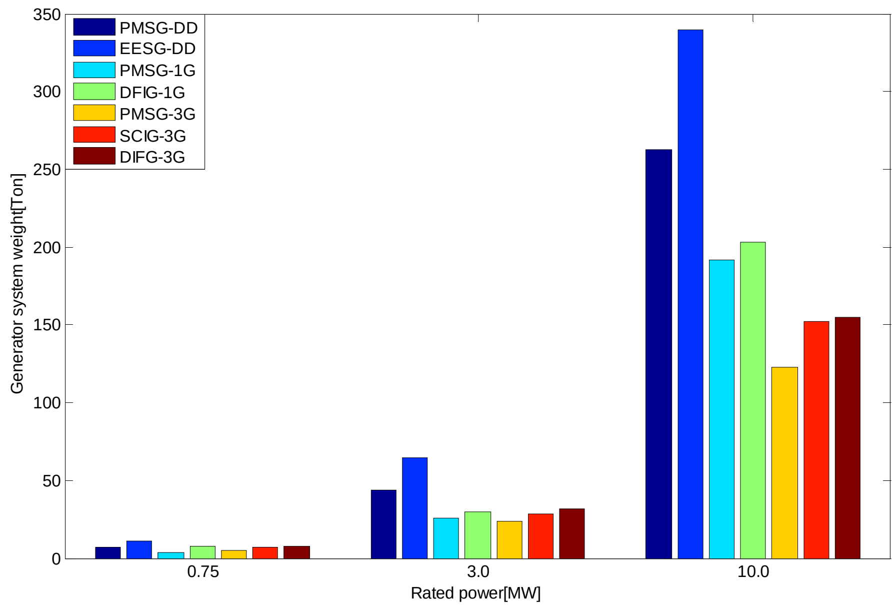


Fig. 6-14: *The system weight of different wind generator systems*

3. Annual energy yield

Fig.6-15 depicts the annual energy yield of the different wind generator systems. The comparison shows that the direct-drive wind generator has the highest energy yield; however, it is only a few percent higher. Therefore, the energy yield of different wind generator systems is almost the same level at a given rated power.

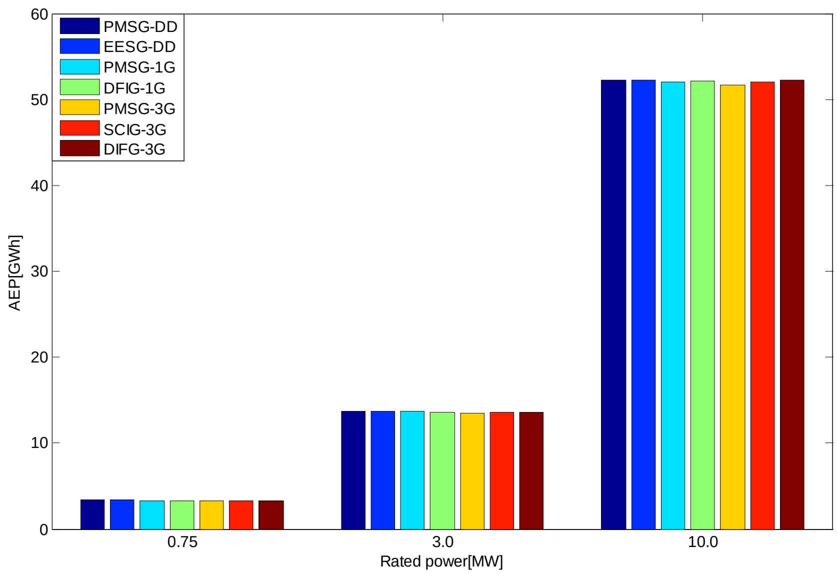


Fig. 6-15: *The annual energy yield of different wind generator systems*

4. AEP per cost

Fig.6-16 depicts the AEP per cost of the different wind generator systems. It can be seen the single-stage geared wind generator systems (DFIG_1G and PMSG_1G) have the highest AEP per cost at small and medium rated power levels, however, when the rated power increased towards 10-MW, the DFIG_3G and DFIG_1G systems seem to be more attractive solutions. In addition, it can be also observed that the EESG_DD system has the lowest AEP per cost for each rated power level.

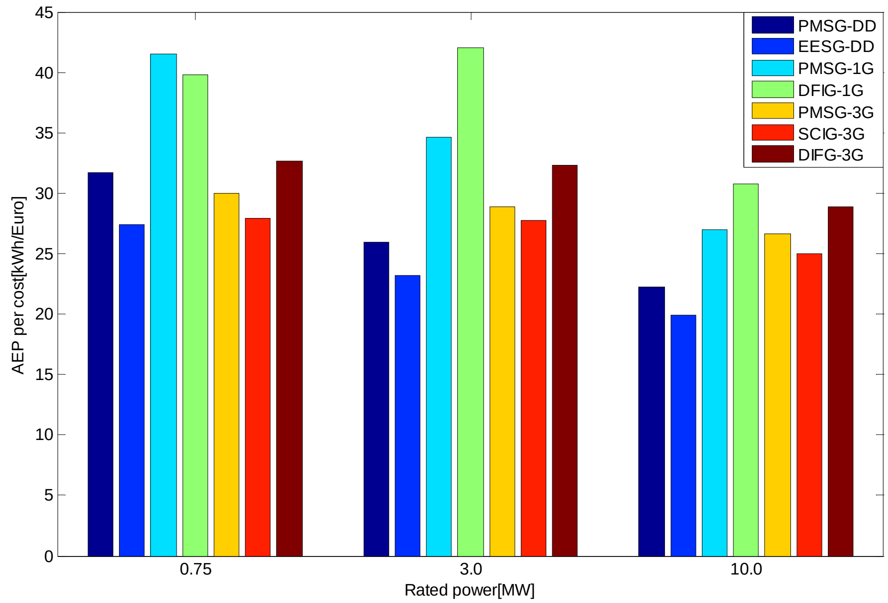


Fig. 6-16: *The AEP per cost of different wind generator systems*

From the above evaluation of all investigated wind generator systems, it can be seen that the wind generator system with the single-stage gearbox seems the most attractive choice, especially for the DFIG_1G system, it has the highest AEP per cost at 3-MW rated power. In addition, the EESG_DD system has the lowest AEP per cost.

6.5 Summary

In order to allow a convenient comparison and investigate the most cost-effective wind generator system, this section summarizes the results presented in sections 2 through 5. According to the classification of wind turbine drive-train types, the performances of the direct-drive wind generator systems, the single-stage geared wind generator systems and the three-stage geared wind generator systems are summarized and evaluated. As examples of small, middle, large rated powers of wind generator systems, the performances of the above investigated wind generator systems are also compared. By the above evaluation of the different wind generator systems, the following conclusions could be made:

•direct-drive wind generator systems: The PMSG_DD system is the more cost-effective choice, because it has lower active material weight, the cheaper generator system cost, the higher energy yield and the higher AEP per cost. In addition, from the viewpoint of the AEP per cost, the direct-drive wind generator system with small rated power may be more attractive.

•single-stage gearbox drive-train concepts: The DFIG_1G system seems to be the more attractive alternative, because it has the lower generator system cost, the higher energy yield and the higher AEP per cost, even though it has a slightly heavier in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the most cost-effective DFIG_1G system is around 1.5MW. The DFIG_1G will keep a higher level in the AEP per cost from 1.5-MW to 5-MW.

•three-stage gearbox drive-train concepts: The DFIG_3G system seems to be the most attractive choice among three wind generator systems; because it has the lowest generator system cost, the highest energy yield and the highest AEP per cost, even though it has a slightly heaviest in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the PMSG_3G system is more interesting than the SCIG_3G system. Furthermore, the most cost-effective wind generator system with the three-stage gearbox may occur around 1.5MW.

Furthermore, by making the numerical evaluation of the investigated wind generator systems at the small, medium and large rated power levels, it can be seen the wind generator system with the single-stage gearbox seems to be the most attractive choice, especially for the DFIG_1G system, it has the highest AEP per cost at 3-MW rated power. In addition, the DFIG_3G system could be the most suitable choice at the large power rating.

7. Conclusions

To evaluate different wind generator configurations, seven types of variable speed constant frequency wind generator systems are investigated, including the direct-drive wind generator systems (PMSG_DD and EESG_DD), the single-stage gearbox drive-train concepts (PMSG_1G and DFIG_1G), and the three-stage gearbox drive-train concepts (PMSG_3G, SCIG_3G and DFIG_3G). The basic characteristics and the analytical design models for different generators have been presented in Report 1. In this report, the possible wind turbine topologies of the investigated generator types have been introduced. The optimization models have been developed for various wind generator systems. The optimization designs for different wind generator systems have been implemented by the IGA. The optimization results are compared and analyzed. The most cost-effective wind generator systems have been evaluated.

7.1 Generator design and optimization

In order to evaluate the performances of the different wind generator systems, it is necessary to use the optimization methods to design. In this report, the IGA is applied for the design optimization of different wind generator systems. The IGA procedure and some optimization examples have been presented in subsection 1.3.2. In order to demonstrate the analytical models of various wind generator systems and the optimization method, a 500-kW direct-drive PMSG is optimized by the IGA. The comparative results have shown that the analytical design models of PMSG and the presented optimization methods are validation. In addition, the analytical models of the single-stage gearbox and three-stage gearbox have been also demonstrated by comparison with some practical data from the manufactures. Furthermore, the suitable ranges of the gear ratio for the optimized PMSG_1G systems have been investigated, which may be useful to design this wind generator concept.

7.2 Evaluation of different wind generator systems

Based on the analytical models of various wind generator systems, the optimization designs have been implemented for designs at the rated powers of 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW, respectively. The evaluations of various wind generator systems have been analyzed by the optimization results. The used criteria include the generator system cost, the generator system weight, the annual energy yield and the AEP per cost, and so on.

1. *Evaluation of the same generator systems with different drive trains*

•*three wind turbine concepts of PMSG systems*: The PMSG_DD system appears to be the most expensive alternative. Compared to the PM generator systems with gearbox (PMSG_1G, PMSG_3G), it has the highest energy yield; however, the AEP per cost is the lowest. It could be a good solution to reduce the cost of the large direct-drive PM generator by integration a gearbox. When the rated power is less than 5MW, the PMSG_1G system appears to the cheapest solution, however, with the rated power further increase, the cost of PMSG_3G system may be cheaper than that of the PMSG_1G system, this is because the cost of the single-stage gearbox rapidly increase under the condition of the larger output torque of gearbox. In addition, the annual energy yield of the PMSG_1G system is higher than that of the PMSG_3G system due to the higher losses in the three-stage gearbox. Therefore, the PMSG_1G have the highest AEP per cost. However, when the rated power increases towards 10-MW, the PMSG_3G system may become more cost-effective choice.

•*two wind turbine concepts of DFIG systems*: The DFIG_1G system appears to be the cheaper alternative, however, it may more expensive than the DFIG_3G system when the rated power increases towards 10-MW, because the cost of the single-stage gearbox is slightly small than that of the three-stage gearbox at the rated power of 10-MW. Due to higher losses in the three-stage gearbox, the DFIG_3G system has lower annual energy yield; however, the annual energy yield is only slightly low, because the generator losses system is further low. From the viewpoint of the AEP per cost, the DFIG_1G system seems to be more attractive choice due to the lower cost and losses in the single-stage gearbox. In addition, the rated power of the most cost-effective DFIG systems may be around 1.5MW.

2. Evaluation of different generator systems with the same drive-train concept

•*direct-drive wind generator systems*: Compared to the EESG_DD system, the PMSG_DD system is more cost-effective choice, because it has lower active material weight, the cheaper generator system cost, the higher energy yield and the higher AEP per cost. In addition, the direct-drive wind generator system has low AEP per cost as the wind turbine size increases; however, the improvement of PMSG_DD system may be more obvious in comparison with the EESG_DD system as the rated power increases.

•*single-stage gearbox drive-train concepts*: The DFIG_1G system seems to be more attractive alternative, because it has the lower generator system cost, the higher energy yield and the higher AEP per cost, even though it has a slightly heavier in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the most cost-effective DFIG_1G system is around 1.5MW. The DFIG_1G will keep a higher level in the AEP per cost from 1.5-MW to 5-MW.

•*three-stage gearbox drive-train concepts*: The DFIG_3G system seems to be the most attractive choice among three wind generator systems; because it has the lowest generator system cost, the highest energy yield and the highest AEP per cost, even though it is slightly heaviest in the term of the generator active material weight. In addition, from the viewpoint of the AEP per cost, the PMSG_3G system is more interesting than the SCIG_3G system. Furthermore, the most cost-effective wind generator system with the three-stage gearbox may occur around 1.5MW.

3. Evaluation of different wind generator systems

As the examples of small, medium and large wind turbine sizes, the performances of all investigated wind generator systems are evaluated for designs at 0.75-MW, 3-MW and 10-MW, respectively. The comparative results have shown that the wind generator system with the single-stage gearbox seems to be the most attractive choice, especially for the DFIG_1G system, it has the highest AEP per cost at the 3-MW rated power. In addition, the DFIG_3G system could be the most suitable solution at the large power rating.

It should be mentioned that the presented design in this study is mainly limited to the generator part. In addition, the generator system cost is rough estimated, and the specific costs of gearbox, power electronics and generator active materials may vary depending on the market. These factors have a significant effect on the optimization results, so that the obtained indexes may not be necessarily to reflect exactly practical performances. However, the developed optimal design procedures and the optimized results may still be useful as a guide for designing various wind generator systems. Furthermore, the numerical evaluation could be helpful to make a judicious choice of the most cost-effective wind generator system for the wind power developer or the power utilities, when carrying out the planning of wind power station installation or developing next generation of wind power conversion system.

7.3 Future work

Evaluation of various wind turbine systems topologies is a delicate task, because different generator systems have different constructing and generating principles. Even though optimization designs and evaluations of various wind generator systems have been addressed in this study, the presented designs are mainly limited to the generator part, for an overall system optimization and evaluation, many other issues need to be considered in the future work. Some of the further topics may include the following.

•Current trends of research and development of wind turbine concepts are mostly related to offshore wind energy. The most important difference between the requirements for onshore and offshore wind energy is that the robustness and maintenance-free are more important feature for offshore wind turbines, because it is extremely expensive and difficult and even impossible to do offshore maintenance and reparations under uncertain weather conditions. So the reliability and availability of large wind turbines may be important aspects to be taken into consideration as a numerical evaluation.

•With the increasing penetration of wind energy into the grid, some performances related with grid connection requirements may need to be considered into quantitative comparisons. For example, the solution of the flicker problem may yield an extra cost depending on topologies of different wind generator systems. The fault ride-though capability is also strongly related to configurations of different wind generator systems. In addition, the ability of flexible power control and advanced protection systems may need to be considered to make more suitable evaluation.

•In this study, the design optimization and comparison of the radial-flux PMSG with surface mounted magnets have been presented. In order to evaluate the most cost-effective wind generator system, different topologies of PMSG and the possible novel generators may be further investigated to make an overall numerical evaluation.

In a word, the further development of variable speed wind turbine concepts would be focused on optimized turbines and thus moving towards more cost-effective machines. An overall and practical evaluation of various wind generator systems, including techniques, economy, control function, availability and reliability may require further investigation.

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