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Design Optimization and Evaluation of Different Wind Generator Systems

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Abstract- **With rapid development of wind power technologies and significant growth of wind power capacity installed worldwide, various wind generator systems have been developed and built. The objective of this paper is to evaluate various wind generator systems by optimization designs and comparisons. In this paper, seven variable speed constant frequency (VSCF) wind generator systems are investigated, namely permanent magnet synchronous generators with the direct-driven (PMSG_DD), the single-stage gearbox (PMSG_1G) and three-stage gearbox (PMSG_3G) concepts, doubly fed induction generators with the three-stage gearbox (DFIG_3G) and with the single-stage gearbox (DFIG_1G), the electricity excited synchronous generator with the direct-driven (EESG_DD), and the VSCF squirrel cage induction generator with the three-stage gearbox (SCIG_3G). Firstly, the design models of wind turbines, three/single stage gearbox and power electronic converter are presented; design optimizations of the investigated wind generator systems are developed with an improved genetic algorithm. Next, the optimization designs are implemented of various wind generator systems at 0.75-MW, 1.5-MW, 3.0-MW, 5.0-MWand 10MW, respectively. The annual energy production (AEP) per cost are evaluated for a given wind climate. The comparative results show the wind generator system with the single-stage gearbox could be the most attractive choice, especially the DFIG_1G system.**

I. INTRODUCTION

More cost-effective and reliable large wind generator systems are becoming increasingly attractive in order to make wind energy to have better competition with other more traditional sources of electrical energy like coal, gas and nuclear generation. Various wind turbine concepts and wind generators have been developed during last two decades. Based on the construction of drive trains, these wind turbine concepts may be classified into the geared drive and direct drive concepts. Furthermore, various types of generators have been applied, such as permanent magnet synchronous generator (PMSG), doubly fed induction generators (DFIG), electrically excited synchronous generator (EESG) and squirrel cage induction generators (SCIG). Therefore, considering possible drive train concepts, various wind turbines have been on the market with various rated power levels. Firstly, a multi-stage gearbox, a DFIG and a power electronic converter feeding the rotor winding with a power rating of approximately 30% of the rated power of the turbine have been adopted by most manufacturers. The largest capacity for the commercial wind turbine product with DFIG has increased towards 5MW from Repower. Next, the direct-drive concepts with a power electronic converter of the full rated power for the grid connection, which reduces the failures in gearboxes and lowers maintenance requirements. Thirdly, an interesting alternative may be a mixed solution with a single-stage planetary gearbox and a medium-speed generator. This concept has gained the attention because it has the advantages as the lower generator cost than the direct-drive concept, and the lower gearbox cost, higher availability and operating reliability than the multiple-stage geared drive concept. Currently, wind turbine manufacturers, such as Multibrid (MB5000-116) and WinWinD (WWD-3) have the PM generator with a single-stage gearbox on the market [2]. Furthermore, variable speed multiple-stage geared concepts with the full-scale power electronic converter (PMSG or SCIG) have also been used by some manufactures [1]. In addition, because the rating of the converter could be reduced to roughly 30%, giving an important benefit in cost and efficiency, a new concept of a DFIG with a single-stage gearbox have been also proposed [3].

This paper presents a numerical comparative evaluation for seven types of wind generator systems as described in Table I.

In order to compare the performances of various wind generator systems at different power levels, the wind turbine generator systems with five power ratings of 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10-MW are investigated, respectively. In this paper, firstly, evaluation models of the wind turbine, the gearbox, the converter and the generator are briefly described. Next, the optimizations method and procedure with an improved genetic algorithm are presented. Finally, the obtained cost and annual energy per cost of the optimized wind generator systems are compared for a given wind climate.

TABLE I
THE INVESTIGATED WIND GENERATOR SYSEMS

Concept	Gearbox	Generator configurations	Abbreviation
Direct-drive	None	PMSG	PMSG_DD
		EESG	EESG_DD
Geared-drive	Single-stage	PMSG	PMSG_1G
		DFIG	DFIG_1G
	Three-stage	PMSG	PMSG_3G
		DFIG	DFIG_3G
		SCIG	SCIG_3G

II. MODELS OF DESIGNING WIND GENERATOR SYSTEMS

In this section, the analytical models of the components of wind generator systems are presented, including the wind turbine power characteristics, the single-stage, and three-stage gearbox, the power electronic converter and the basic electromagnetic design models of generators:

A. Wind Energy Production

The available shaft power, P_T from a wind turbine can be calculated as a function of the wind speed [4]

$$P_T = \frac{1}{8}\rho C_p(\lambda,\beta)\pi D^2 v^3 \tag{1}$$

where ρ is the air density, D is the wind turbine rotor diameter, v is the wind speed, and $C_p(\lambda,\beta)$ is the power coefficient or aerodynamic efficiency, which is a function of the tip-speed ratio, λ and the pitch angel of turbine blades, β.

In this case, the shaft power is assumed to be proportional to the cube of the wind speed at the maximum aerodynamic efficiency, $C_{p\max}$ below the rated wind speed. Above the rated wind speed, the blades are pitched to reduce the aerodynamic efficiency, and so that the shaft power is kept as a constant. Thus, the rated wind speed can be calculated as

$$v_N = \sqrt[3]{\frac{8P_{TN}}{\pi\rho C_{p\max} D^2}} \tag{2}$$

where P_{TN} is the rated shaft power, which can be obtained from the generator design.

Table II gives the main parameters for the comparative study of various wind generator systems.

TABLE II
MODELING PARAMETERS OF WIND GENERATOR STSTEMS

Wind turbine modeling					
Rated power P_N [MW]	0.75	1.5	3.0	5	10
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Rotor diameter D [m]	50	70	90	116	170
Swept area [$\times 10^3$ m^2]	1.96	3.85	6.36	10.6	22.7
Hub height mean wind speed [m/s]	10.3	10.9	11.3	11.8	12.8
Hub height [m]	60	84	108	138	204
Cut in wind speed v_i [m/s]			2.5		
Cut out wind speed v_c [m/s]			25		
Optimum tip speed ratio λ_{opt}			7		
Maximum power coefficient C_{pmax}			0.48		
Air density [kg/m^3]			1.225		
Loss modeling					
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 kc				3%	
Cost modeling					
A single-stage gearbox service factors F_s				1.25	
Planet wheels number in a single–stage gearbox Z				6	
Specific cost of a single-stage gearbox c_{gear_1} [Euro/kg]				6	
Specific cost of a three-stage gearbox c_{gear_3} [Euro/kg]				10	
Specific cost of copper c_{cu} [Euro/kg]				15	
Specific cost of NdFeB magnets c_m [Euro/kg]				40	
Specific cost of reference 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	

For energy yield calculations, the energy contribution at each wind speed can be determined by the product of the power output $P_{grid}(v)$ of the wind generator system at the specific wind speed and the duration that the wind speed occurs annually. Therefore, the annual energy production (AEP) can be estimated by summing the incremental energy contributions at each wind speed, which can be expressed:

$$AEP = 8760 \cdot \int_{v_i}^{v_c} P_{grid}(v)\cdot f(v)\, dv = 8760 \sum_{j=1}^{n} P_{grid}(v_j)\, f(v_j)\Delta v \tag{3}$$

where $f(v)$ is taken as Weibull density distribution, which is given as [4]

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{(-(v/c)^k)} \qquad (k>0,\ \ c>1) \tag{4}$$

where k is the shape parameter and c is the scale parameter.

The wind speed of candidate sites is usually measured at 10m anemometer height. If these heights do not match the hub height of a wind turbine, it is necessary to extrapolate the wind speeds to the hub height of the turbine. The extrapolated wind speed, v_H corresponding to the hub height is given as [4]

$$v_H = v_0 (H/H_0)^{\alpha} \tag{5}$$

where v_0 is the wind speed at height $H_0 = 10$ m above the ground level α is the power index constant. In this case, α is assumed to be 1/7.

The majority of wind farm sites around the world have the annual mean wind speeds in the range of 6-8m/s at 10m height. In this case, the hub height of wind turbine is approximately calculated with 1.2 times turbine blades diameter. A specific site with an average wind speed of 7m/s at 10m height $(k=2, c=7.9)$ is used. The AEP of different wind generator systems can be evaluated by the annual mean wind speeds calculated at the hub height as shown in Table II.

B. Gearbox Weight and Power Loss

As the gear ratio increases, the increased generator speed reduces the size and the cost of the generator. However, higher gearbox ratios increase the gearbox mass and cost, so that weight and cost models of the gearbox have to be considered.

The weight of a single stage gearbox depends upon the stage ratios chosen and the shaft torque level, which can be given as

$$G_{gear\_1} = 3.2 T_m\, F_s\, F_w / 1000 \tag{6}$$

where T_m is the output torque of the gearbox (Nm); F_s is service factor considering surface damage and failure by metal fatigue. The weight factor, F_w is given as [4]

$$F_w = \frac{1}{Z} + \frac{1}{Z\cdot r_w} + r_w + r_w{}^2 + 0.4\frac{(1+r_w)}{Z}(r_{ratio}-1)^2 \tag{7}$$

where Z is the planet wheel number in a stage; the wheel ratio $r_w = \frac{r_{ratio}}{2} - 1$, r_{ratio} is the single-stage gear ratio.

Because the rated generator speed of the wind generator systems with a three-stage gearbox is assumed to be 1200rpm, the mass weight for the three-stage gearbox is roughly scaled based on the low-speed shaft torque [5].

$$G_{gear\_3} = 10.35\, T_L + 1950 \tag{8}$$

Where T_L is the input mechanical torque of the low speed shaft (kNm).

The losses in a gearbox can be divided into two different parts, one includes gear teeth losses and bearing losses, that depends on the input power, and the other includes seal losses and lubricant losses, which depends on the rotational speed. For the power dependent losses, they are usually modeled as 1% of the input power, so that it is reasonable to neglect [3]. This means that the main losses in a gearbox are proportional to the shaft speed.

$$p_{gear} = k_g\, P_N\, \frac{n_r}{n_{rN}} \tag{9}$$

where k_g is a constant for the speed dependent losses (in this case it is 1.5% for a single-stage gearbox and 3% for a three-stage gearbox, see Table II), P_N is the rated power of wind turbines, n_r is the rotor speed, n_{rN} is the rated rotor speed.

C. Power Electronic Converter Cost and Power Loss

A back-to-back PWM power converter can be used as the interface between the wind generator and grids. As an example, Fig.1 shows the main circuit topology of a back-to-back PWM power converter of PMSG_DD system, which is composed of a generator-side converter, a grid-side converter and a dc-link capacitor. By using the power electronic converter, the variable speed operation of wind generator systems can be realized so that the turbine can operate at its maximum efficiency.

The cost of the power electronic converter may be presented as a function of power converter rating in kW with a constant k_c

$$C_{conv} = k_c\, P_{conv} \tag{10}$$

Where P_{conv} is the power converter rating. For the DFIG systems, it is assumed to 0.3 times the machine power capacity.

The losses in the power electronic converter p_{conv} are modeled as [3]

$$p_{conv} = \frac{p_{convN}}{31}\left(1 + 10\frac{I_s}{I_{sN}} + 5\frac{I_s^2}{I_{sN}^2} + 10\frac{I_g}{I_{gN}} + 5\frac{I_g^2}{I_{gN}^2}\right) \tag{11}$$

where p_{convN} is the dissipation in the converter at the rated power. I_s is the generator side converter current. I_g is the grid side converter current.

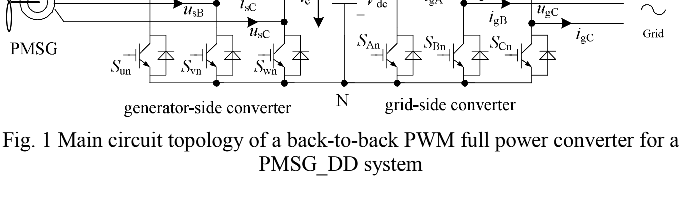


Fig. 1 Main circuit topology of a back-to-back PWM full power converter for a PMSG_DD system

D Generators Parameters Calculation

The analytical methods based on the magnetic circuit and equivalent circuit models are used for electromagnetic design of various generators. This subsection describes the main equations used to determine the parameters of the equivalent circuit. More detailed information may be found in [3-12].

Slot, air-gap and end-winding leakage inductances are calculated as given in [12]. The magnetizing inductance can be given as

$$L_{sm} = \frac{6 \cdot \mu_0 \cdot L_e \cdot r_s \cdot (k_w \cdot N_s)^2}{\pi \cdot p^2 g_{eff}} \tag{12}$$

where k_w is winding factor; N_s is number of turns of the phase winding; ω_m is mechanical angular speed of the rotor; r_s is air gap radius; L_e is an equivalent core length; μ_0 is the constant of the permeability of vacuum; p is the number of pole pairs; g_{eff} is the effective gap, which depends on the type of machine. For all machine types, it can be written as

$$g_{eff} = k_{cs} \cdot k_{cr}\, (g + \frac{h_m}{\mu_{rm}}) \tag{13}$$

where k_{cs}, k_{cr} are the Carter factors for the stator slots and the rotor slots (if present), g is the mechanical air gap, μ_{rm} is the relative recoil permeability of the magnets, and h_m is the magnet length in the direction of the magnetization (which is zero in a machine without permanent magnets)

The no-load voltage induced by the fundamental air-gap flux density B_{g1} in a stator winding can be calculated as

$$E_p = \sqrt{2}\, k_w \cdot N_s \cdot \omega_m \cdot r_s \cdot L_e \cdot B_{g1} \tag{14}$$

where ω_m mechanical angular speed of the rotor.

The iron losses are approximated with Steinmetz formula [12]

$$p_{Fe} = 2\, p_{Fe0h} \cdot (\frac{f_e}{f_0})(\frac{\hat{B}_{Fe}}{\hat{B}_0})^2 + 2\, p_{Fe0e} \cdot (\frac{f_e}{f_0})^2 (\frac{\hat{B}_{Fe}}{\hat{B}_0})^2 \tag{15}$$

where f_e is the frequency of the field in the iron, p_{Fe0h} and p_{Fe0e} are the specific hysteresis loss and the specific eddy current loss (in W/kg) in the laminated stator core for a given frequency f_0 (50Hz) and a flux density $\hat{B}_0$ (1.5T)

III. OPTIMIZATION MODELS OF VARIOUS WIND GENERATOR SYSTEMS

This paper presents a comparative study of the numerical optimization results of various wind generator systems for different power levels. In this section, the optimization models are described, some features and assumptions are also taken into account. A genetic algorithm is used as the optimization method.

A. Objective function

In order to obtain the most cost-effective wind generator system, the proposed criterion is the generator system cost

$$C_w = C_{g\_act} + C_{g\_str} + C_{con} + C_{subsystem} + C_{gear} \tag{16}$$

where $C_{g\_act} = c_{cu} G_{cu} + c_{Fe} G_{Fe} + c_m G_m$ is generator active material cost; c_{cu}, c_{Fe}, c_m are the unit costs of the copper, the active iron and the permanent magnets (if present), respectively; G_{cu}, G_{Fe}, G_m are the weight of the copper, the active iron and the permanent magnets (if present), respectively. C_{g_str} generator structure 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 [6]. C_{con} is cost of power electronic converter. $C_{subsystem}$ is 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 used specific component costs are given in Table III, respectively.

B. Optimized variables and some assumptions

In order to optimize each wind turbine generator system for the minimum generator system cost (16), 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 following assumptions are used in the optimization program:

- The number of slots per pole per phase is $q = 1$ for the PMSG system, in order to allow for a small pole pitch without getting a low slot fill factor because of narrow slots. In addition,
- The number of slots per pole per phase is $q = 2$ for the EESG system.
- The rated generator speed is assumed to be 1200rpm for the DFIG_3G systems at different rated power levels. 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.
- 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 slot filling factor is set as a constant value, i.e. it is 0.55 for the stator outer diameters larger than 2m; below 2m, it is assumed to be 0.45.
- 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 [6] [7] [12].
- 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 [12].
- 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. 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.

C. Optimization methods

The genetic algorithm (GA) has high probability of locating the global optimum in a multidimensional searching space discarding all existing local optimal solutions [13]. 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.

$$F(X) = f(X) + \sum_i a_i \left[\max(0, g_i(X)) \right]^2 \tag{17}$$

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

In this study, an improved genetic algorithm (IGA) is used to optimize the investigated wind generator systems, which has been developed and applied to the design optimization of induction machines and power transformers in previous work [14] [15]. In the IGA model, each string (chromosome) is expressed by the real number code for the chosen optimal design variable; the stochastic crossover method incorporating the arithmetic crossover technique and the uniform crossover scheme is developed to increase the solution space and speed up the convergence of optimization; the crossover rate and mutation rate can dynamically varies with the processing of optimization. The convergent condition of IGA is chosen as either the maximal number of generations or the average solution quality.

IV. OPTIMIZATION RESULTS AND EVALUATION

In order to compare various wind generator systems at different rated power levels, the mentioned analytical models are used to optimize several generator systems. In this paper, five rated power levels of 750-kW, 1.5-MW, 3.0-MW, 5.0-MW and 10.0-MW are reported. In order to allow a convenient comparison of various wind generator systems, the comparisons based on the AEP per cost are summarized for each power level for the different types of wind turbine drive trains at five power levels. Then, the performances of all the investigated wind generator systems are presented at three power levels, so that the most cost-effective wind generator systems can be identified.

A. Evaluation of direct-drive wind generator systems

Fig. 2 shows the AEP per the generator system cost of the optimal designed direct-drive PMSG and EESG systems. In this case, the increased or decreased percentages of the performances of the PMSG_DD system are also presented with

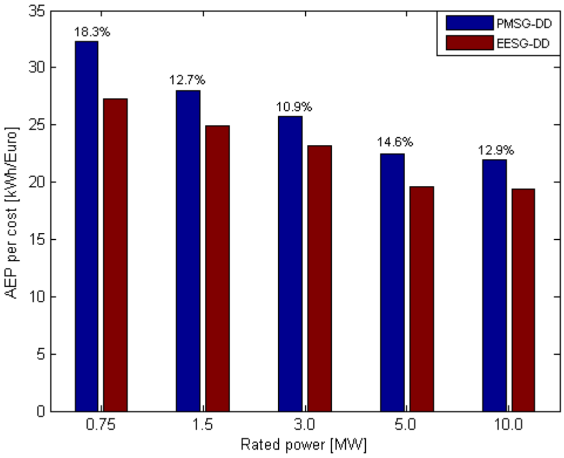


Fig. 2 The AEP per cost of direct-drive wind generator system

reference to the EESG_DD system. 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 14% improvement because the PMSG_DD system has higher generator efficiency without the additional rotor copper losses.

B. Evaluation of a single-stage geared drive generator systems

Fig. 3 shows the AEP per cost of the optimal designed PMSG_1G and DFIG_1G systems. In this case, the increased or decreased percentages of the performances of the PMSG_1G system are also presented with reference to the DFIG_1G system. 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.

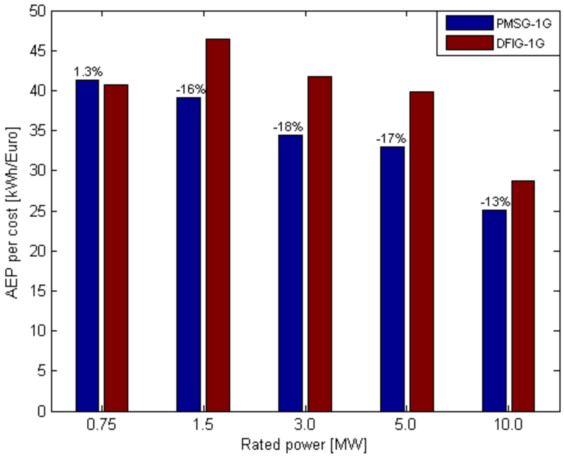


Fig. 3 The AEP per cost of a single-stage geared drive wind generator systems

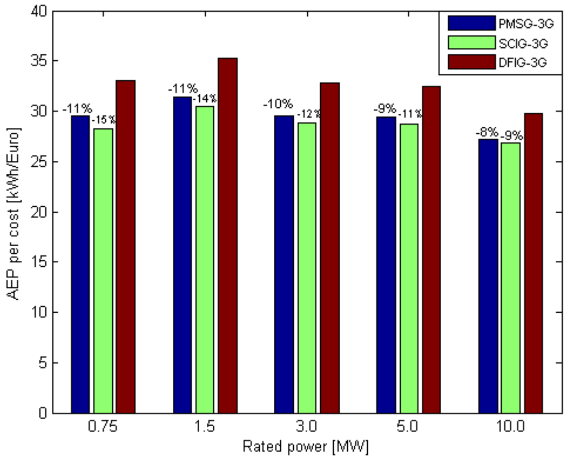


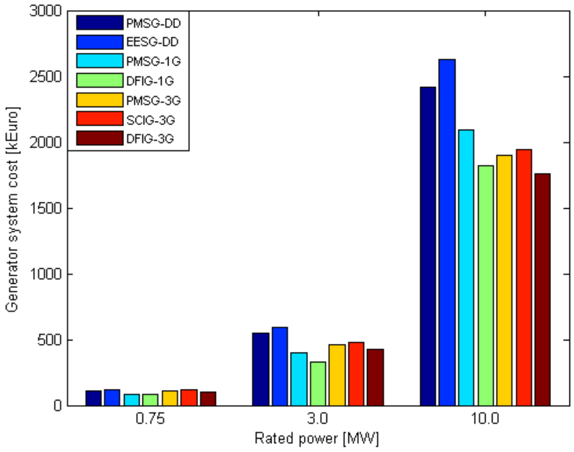
Fig. 4 The AEP per cost of different generator systems with the three-stage gearbox

C. Evaluation of the three-stage geared drive wind generator systems

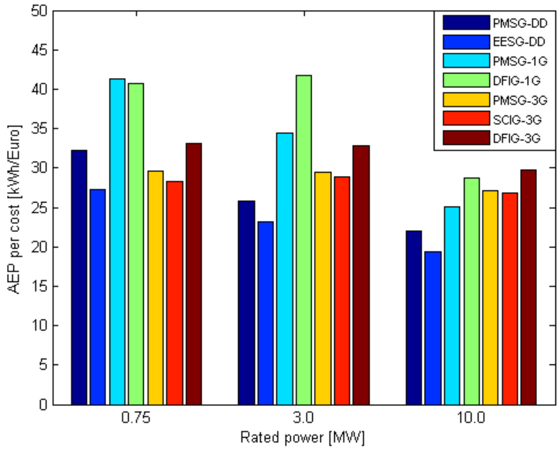
Fig. 4 shows the AEP per cost of the PMSG_3G, SCIG_3G and DFIG_3G systems for each optimal design. It can be also seen the DFIG_3G system has the highest AEP per cost, whereas the PMSG_3G system is higher than the SCIG_3G system. Compared with the DFIG_3G system, the PMSG_3G system could reduce over 10%, whereas for the SCIG_3G system may decrease nearly around 13%. In addition, the power level of the most cost-effective wind generator system with the three-stage gearbox may be around 1.5-MW, regardless of the PMSG_3G, SCIG_3G and DFIG_3G systems.

D. Evaluation of the investigated wind generator systems

In order to further evaluate the performances of various wind generator systems, the generator system cost and AEP per cost of all investigated wind generator systems are summarized in Figs. 5(a) and (b). In this case, the comparisons are focused on the rated power of 0.75-MW, 3.0-MW and 10-MW. 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_3G 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. On the other hand, 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.



(a) The generator system cost



(b) AEP per cost

Fig. 5 The comparison of seven wind generator systems

V. CONCLUSIONS

The design optimization of seven VSCF wind generator systems (PMSG_3G, PMSG_1G, PMSG_DD, DFIG_3G, DFIG_1G and SCIG_3G) have been investigated in this paper. By the comparison based on the generator system cost and AEP per cost, the following conclusions may be drawn:

(1) Direct-drive wind generator systems: Compared to the EESG_DD system, the PMSG_DD system is more cost-effective choice, because it has lower generator system cost 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.

(2) Single-stage gearbox drive-train concepts: The DFIG_1G system seems to be more attractive alternative, because it has the lower generator system cost and the higher AEP per cost. 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.

(3) Tthree-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 and the highest AEP per cost. In addition, from the viewpoint of the AEP per cost, the PMSG_3G system is more interesting than the SCIG_3G system.

(4) Furthermore, by making a comparison of all the investigated wind generator systems at three power levels, the 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.

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