552 Journal of Electrical Engineering & Technology, Vol. 3, No. 4, pp. 552~558, 2008

Optimal Design of a Direct-Driven PM Wind Generator Aimed at Maximum AEP using Coupled FEA and Parallel Computing GA

Hochang Jung*, Cheol-Gyun Lee, Sung-Chin Hahn* and Sang-Yong Jung†**

Abstract – Optimal design of the direct-driven Permanent Magnet (PM) wind generator, combined with F.E.A (Finite Element Analysis) and Genetic Algorithm (GA), has been performed to maximize the Annual Energy Production (AEP) over the entire wind speed characterized by the statistical model of wind speed distribution. Particularly, the proposed parallel computing via internet web service has contributed to reducing excessive computing times for optimization.

Keywords: Annual Energy Production (AEP), Genetic Algorithm (GA), parallel computing, PM wind generator.

1. Introduction

The direct-driven wind generator that operates without the use of reduction gear has been developed dramatically, mainly on account of weight effectiveness, low noise generation, low maintenance cost, and etc. One of the attractive solutions for the direct-driven wind generator is the Surface-Mounted PM Synchronous Generator (SPMSG), which shows the distinctive advantages of higher efficiency, torque density, and size [1,2]. In this paper, optimal design of the direct-driven SPMSG is considered using GA coupled with F.E.A for better accuracy and reliability. Whereas the conventional design of a wind generator has concentrated on the efficiency improvement or larger power production at the rated speed, the proposed optimal design of SPMSG is aimed for maximizing the AEP of the direct-driven SPMSG considering the overall operating wind speed. Furthermore, the statistical Rayleigh distribution of the operating wind speed, well-known function for its good approximation to the real wind power circumstances, is applied for optimization [3-5].

Meanwhile, many complex optimization problems related to virtual engineering cannot be formulated analytically. It is typical that the objective function and the constraints are highly nonlinear. Examples of such engineering problems are the shape and structural design of the electric machine. It is required to use the finite element method (FEM) to calculate the performance of the machine correctly and to consider saturation of the flux path. It has much longer computation time than the lumped parameter method. Moreover, a stochastic optimization technique such as genetic algorithm (GA) creates multiple numbers of candidates for each optimization step. Additionally, the applied optimal design requests the F.E.A simulation for every evaluation of the objective function and the constraints, which in turn causes the excessive execution time. Inherently, computational time has been saved with assistance of the distributed parallel computing method via internet web services. Instead of using the traditional parallel hardware such as the vector computer, distributed parallel computing can be realized based on the internet web services. This type of method has many advantages, such as ease of communication, reliability, firewall friendliness, and access to a number of computers via the Internet [6,7].

In this paper, the ultimate goal is the optimal design of SPMSG for 500kW using GA coupled with F.E.A. Accordingly, the optimal design results of SPMSG for maximizing AEP are compared with the conventional model [8]. Not only the generated power and energy but the efficiency versus wind speed is compared, which manifests the effectiveness of AEP maximization for a wind generator application after all [9].

2. Wind Power Generation and Design Specification

2.1 Characteristics of Wind Power Generation

This output of the wind turbine (P_S), transmitted to a wind generator, is converted from the input wind power (P_W) with pitch-controlled blades, which is formulated as follows [1].

$$P_S = C_P(v)P_W = (C_P(v)\rho v^3 A)/2 \quad (1)$$

---

† Corresponding Author: Dept. of Electrical Engineering, Dong-A University Korea. (syjung@dau.ac.kr)

* Dept. of Electrical Engineering, Dong-A University, Korea.

** Dept. of Electrical Engineering, Dong-Eui University, Korea.

Received 29 February 2008 ; Accepted 28 May 2008

where $C_p(v)$: power coefficient according to the wind speed supplied by a turbine manufacturer, ρ : air density [kg/m^3], v : wind speed [m/s], A : blade swept area [m^2].

Since the input of a wind generator (P_i) is equal to P_s in a direct-driven generator, the output current of the generator is calculated as (2) and (3).

$$P_i = P_s = T^e \cdot \omega_m \,, \tag{2}$$

$$i_s = (C_p(v)v^2(\rho\pi R^3))/3(p\lambda_{pm}\lambda(v)) \,, \tag{3}$$

Where $T^e = (3p\lambda_{pm})/2$ [Nm], $\lambda(v) = R\omega_m / v$: tip speed ratio, ω_m: turbine speed[rad/s], R : radius of the turbine blade[m], p : number of pole pairs, λ_{pm} : PM flux linkage [Wb].

Then, the nonlinear 2D FEA with a current source has been carried out to calculate the loss of a wind generator whereby the ultimate wind power generation (P_o) can be obtained by subtracting the obtained loss from (2).

2.2 Wind Speed Distribution

In order to consider the characteristics of various wind speeds, this paper adopts the statistically approached wind speed distribution. Inherently, Rayleigh distribution, which shows good approximation to the real wind power circumstances, has been applied as a probability density function characterized by the average value as follows [3].

$$F(v) = (\pi v)/(2v_a^2)\exp\left[-(\pi/4)(v/v_a)^2\right], \tag{4}$$

where v_a is the average wind speed for the area, and $F(v)$ means the likelihood of a prevailing wind at every speed (v).

2.3 Design Specification and Objective of SPMSG

The most attractive candidate for a direct-driven wind generator may be SPMSG due to its higher efficiency and torque density near low speeds, compatible to direct-driven application. In this paper, a 500kW SPMSG has been applied for the optimal design of which design specifications are summarized in Table I.

Enhancing the wind power generation not only at the specified wind speed, but over the whole operating wind speed, AEP maximization has been applied for the optimal design [3]. At the given speed, the effective operating hour ($H(v)$) can be calculated by using (5) as follows.

$$H(v) = N_t \cdot F(v) \cdot \Delta v \ \text{[h]}, \tag{5}$$

Table 1. Specification of Wind Generation System

Rated Power Output (P_s)		500kW
Wind Speed	Cut-in wind speed	3.5 m/s
	Rated wind speed	13.5 m/s
	Cut-out wind speed	26 m/s
Generator	Type	SPMSG
Turbine	Diameter	39 m
	Rotational speed range	0~32 rpm
	Blade swept area	1207m^2
	Control System	Pitch Control

where N_t denotes the total number of annual operating hours within a year.

Once the total operating hours at the given wind speed is specified, the total amount of energy production covering the total operating wind speed can be modeled as follows, which will be the ultimate objective of the optimal design of SPMSG.

$$AEP = \sum_{v=0}^{n} P_o \cdot H(v) \ \text{[Wh]} \tag{6}$$

3. Distributed Parallel Computing via Internet Web Service

3.1 PIDC System Architecture

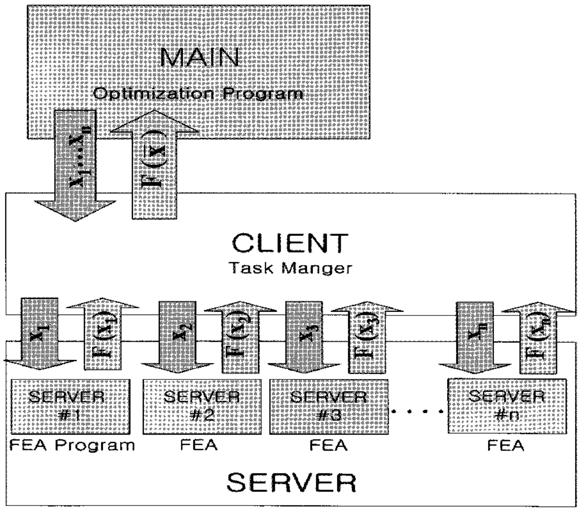


Fig. 1. The system architecture for PIDC

Although the optimal design coupled with F.E.A guarantees the accuracy of the design results, it does not inevitably avoid the excessive execution time for the iterative computation. Worse than that, AEP maximization requests the F.E.A simulation at every wind speed in a single iteration. Hence, the distributed parallel computing has been applied to slacken excessive computation times, inherently based on the internet web service. The contribution of the internet web service is to use a parallel computing resource through the web at a much faster speed than possible on a single computer. Particularly, many repetitive tasks are divided up according to the number of the computers connected via the Internet and the results of the assigned task interface each other rapidly, as shown in Fig. 1. This technique is suitable for any stochastic optimization problem like the proposed optimal design of SPMSG using GA, which has multiple candidates in each step and huge computational loads during the optimal solution search. In this system, calculation of the objective function and the constraints for each candidate can be done independently on the different processors.

3.2 Characteristics of PIDC System

3.2.1 Interface Management

The optimization software must provide an interface to the FEM analysis software which allows to control the FEM analysis and to retrieve data from the FEM simulation model. For instance, the optimization software must be able to set parameters of the FEM analysis model according to certain values of decision variables of the optimization problems. Similarly, after a FEM analysis run is completed, values for objective function and constraints can be obtained from it for optimization.

3.2.2 Synchronizations

If the optimization algorithm has requested the evaluation of a solution vector from the FEM analysis system, the algorithm has to wait for the completion of the FEM analysis. Vice versa, the FEM analysis software has to wait for the next request after finishing the current one. Thus, between these two components at least two processes have to be synchronized, and the data exchange has to be coordinated.

3.2.3 Heterogeneity

The coupled optimization and task manger should be shielded from platform-specific hardware and software matters, such as inter-process / object communication, etc.

3.3 The Proposed PIDC System

The PIDC system consists of the main, task manager, and networked computers. The main has its own user interfaces. Because it is the topmost layer, it has to provide a user interface for the convenient formulation of the optimization problem and probably additional visualization techniques for the results of the optimization. Fig. 2 shows the detailed function diagram of the proposed PIDC system. When the main computer has tasks which should be calculated through FEM simulation, the Task Manager performs a search of networked computers (Search Url()). If it finds computers, it distributes tasks to those that are networked (Copy Process(), Web Copy()). Following that, each networked computer carries out the assigned task (Assist()).

The objective function and other constraints using the FEM program are computed. As soon as a task is completed, each computer calls the Task Manager and the Task Manger assigns another remained task to it. When all of the tasks are done, the Task Manager returns the result to the Main (Get Process()), Web Get()). Finally, Task Manger is initialized by Reset() function and then the optimization program in Main goes next step.

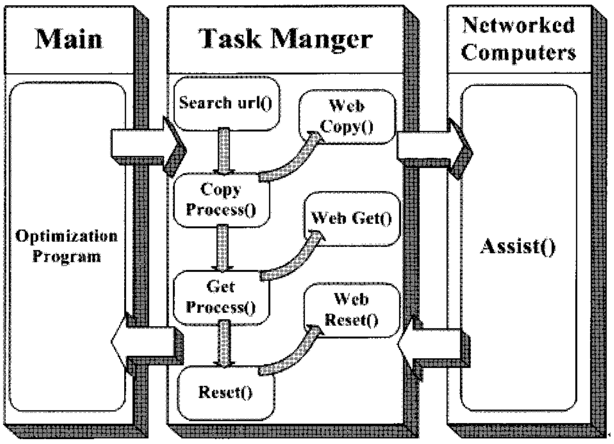


Fig. 2. Function diagram for PIDC

Our proposed PIDC system has the following features. Firstly, it can, quite literally, bring supercomputing power to the hands of ordinary users. Secondly, it is not limited to the number of volunteer computers. Finally, it has the real time monitoring that shows the status of the linked computer and optimization program in the Main computer.

3.4 Internet Web Service

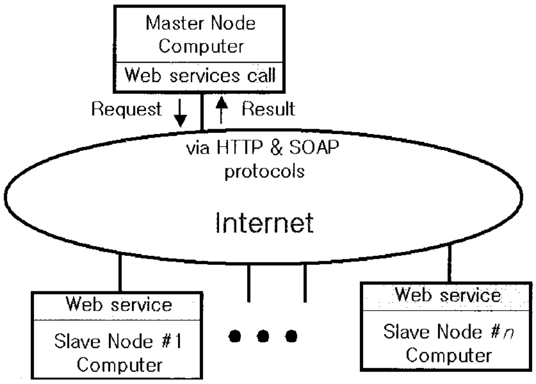


Fig. 3. Internet web service

Internet web service is essential to perform the Distributed Parallel Computing with both accuracy and efficiency. The scheme of Internet web service is shown in Fig. 3.

It shows a master node that distributes independent jobs, and slave nodes that receive and solve the jobs. The communication between master and slave nodes is realized by Internet's HTTP and SOAP protocols using web service. This web service is programmed using Microsoft's .NET solution.

In case of application to optimization, the optimization algorithm is executed in the master node computer and the evaluation of objective function is performed in several slave node computers. The distributed computing, as a form of the web service technology, is different from the MPI (Message Passing Interface) and PVM (Parallel Virtual Machine) technologies, which are, in general, for the local area network, tightly coupled cluster, or parallel environment. It deals with multiple tasks by way of distributing them to the computers linked by Internet as opposed to tackling one big problem and dividing it up to the computers. In addition, it is easy to implement, working with low-bandwidth and different kinds of computers.

3.5 FEA-based Optimization

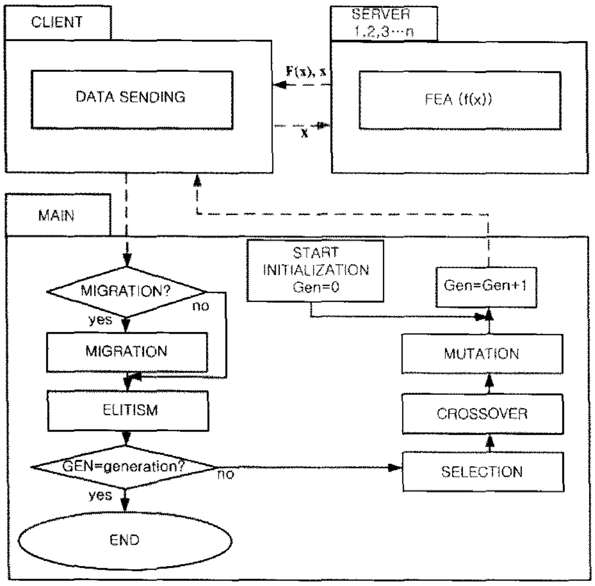


Fig. 4. The combination of GA Module with FEA Module using PIDC

Due to the FEM simulations, the assumptions on convexity and smoothness of objective and constraint functions are no longer valid. Therefore, optimization algorithms with local convergence are not applicable. Furthermore, a global optimum of the problem must be found.

In the case of FEA-based optimization, the optimization module requests a FEM simulation for every evaluation of the objective function and the constraints of the optimization problem. The computation time of a single FEM simulation depends on the complexity of the simulated model and may range from a few seconds up to several hours. Many hundreds or thousands of these FEM simulations lead to very lengthy computation times. To resolve this problem, the parallel or distributed computing technique is needed. The scheme of optimization using PIDC is shown in Fig. 4.

3.6 Numerical Examples

In evaluating the operational characteristics of a parallel algorithm in terms of the required computation, it is usual to define a speed-up factor, S(n), where n is the number of processors forming the multiprocessor system. Here, S(n) is defined as the execution time, T1, of the program (normally the sequential variant) running on a single processor divided by the execution time, Tn, when the parallel version of the program is executed on n processors. An alternative definition, efficiency, E(n), is defined as the average utilization of the n allocated processors comprising the multiprocessor system. Hence, in terms of speed-up, E(n) = S(n)/n.

In order to study the performance of the internet distributed computing, the well-known mathematical benchmark problem based on the Rosenbrock function is used. The 4-dimensional Rosenbrock function is defined as

$$F_4(x)=100(x_1^2-x_2^2)+(1-x_1)^2+90(x_4-x_3^2)+(1-x_3)^2 \\ +10.1\{(x_2-1)^2+(x_4-1)^2\}+19.8(x_2-1)(x_4-1) \quad , \ (7)$$

where $-10 \le x_1, x_2, x_3, x_4 \le 10$,

The minimum is known to be f(x)=0 at all x_i=1.

In contrast to the real world optimization problems in engineering, the evaluation of the objective function for the test function is negligible in terms of computation time. To emulate the conditions of engineering problems, the evaluation of the objective function was artificially delayed to three seconds. For the test, six IBM PCs from one laboratory were used as the networked computers.

Although computers located at longer distances would better serve the purpose of the test involving the Internet protocol, the results are considered to be almost the same except for the differences caused by the factor of network speed. For the GA, the number of individuals of population is 60 and the maximum number of generations is 250. Fig. 5 shows the convergence characteristic when the number of linked computers is three. It demonstrates that the proposed method performs the optimization well.

Fig. 6 indicates that the overall execution time for the optimization decreases according to the number of connected computers. The ideal time is an execution time running on a single computer divided by the number of linked computers. The real time is an execution time using PIDC. The efficiency of PIDC depends on the relative difference between the FEM analysis time and the communication time.

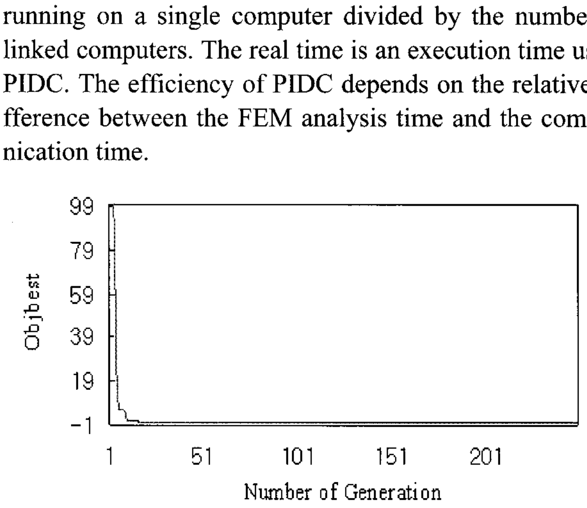


Fig. 5. The convergence characteristic

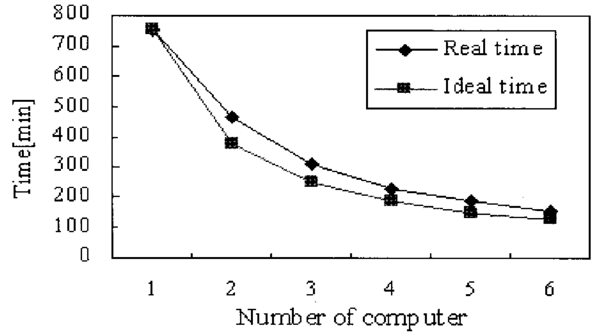


Fig. 6. The overall execution time according to the number of computers

4. Optimal Design of SPMSG using GA Coupled with F.E.A

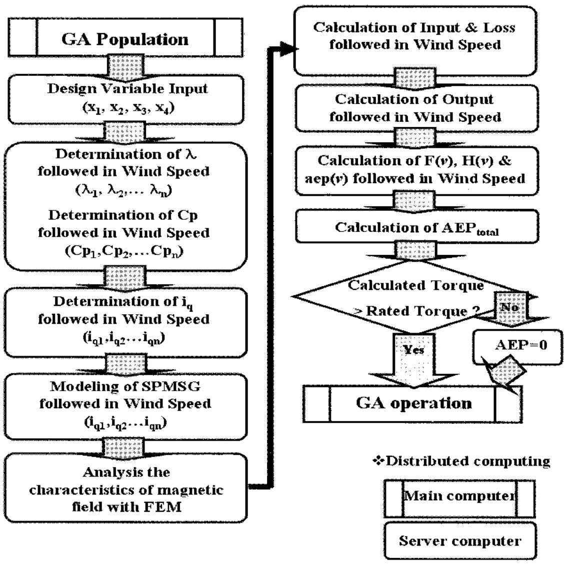


Fig. 7. Flowchart of the optimal design of SPMSG to maximize AEP using GA coupled with F.E.A.

Optimal design of SPMSG, of which the design specification is summarized in Table 1 and the design objective is maximized (6). This can be carried-out using GA coupled with F.E.A computing the loss with the design variables, tip speed ratio($\lambda(v)$), power coefficient($C_p(v)$), and current source of (3) according to the wind speed, as shown in Fig. 7.

Under the fixed outline dimension holding the outer diameter (=1154.9[mm]) and the axial length(=550[mm]), the design variables are selected as the pole-arc angle of PM(x_1), tooth width(x_2), stator yoke depth(x_3), and slot depth(x_4), as shown in Fig. 8. The other dimensions, such as the number of poles (=100) and slots (=300), the residual flux density of PM(Br=1[T]), the air-gap length (=2.15 [mm]), and etc. have been fixed empirically based on the manufacturing feasibility.

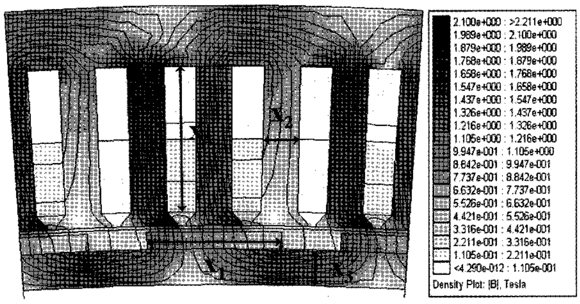


Fig. 8. Design variables of SPMSG (x_1: the pole-arc angle of PM, x_2: tooth width, x_3: stator yoke depth, x_4: slot depth)

In addition, the design constraint is the permissible torque value over 140[kNm] at the rated speed. For reference, the flux density distribution of Fig. 8 is the numerical results of a conventional model.

5. Optimal Design Results of SPMSG Maximizing AEP

The optimal design results of SPMSG for maximizing AEP are compared with the ones designed optimally for maximizing the efficiency at the rated speed. Not only the generated power and energy production but the efficiency versus wind speed is compared, which are shown in Figs. 9, 10, and 11.

In Fig. 9, the generated power increases according to the wind speed with the limit of 509.32[kW] exceeding the rated speed (13.5[m/s]) mainly due to the pitch-control of blades. On the other hand, the energy production in Fig. 10 has the peak values at 11[m/s], which indicates the most frequent and the largest power generation simultaneously. However, this value shows a slight difference to the rated speed, which suggests the careful decision of a rated speed, usually roughly done with the available peak wind speed.

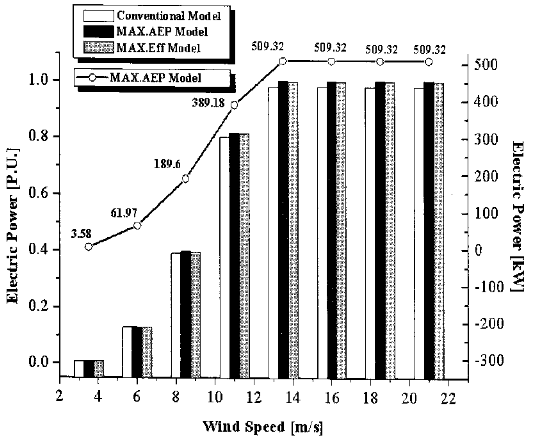


Fig. 9. Comparison results of electric power generation versus wind speed

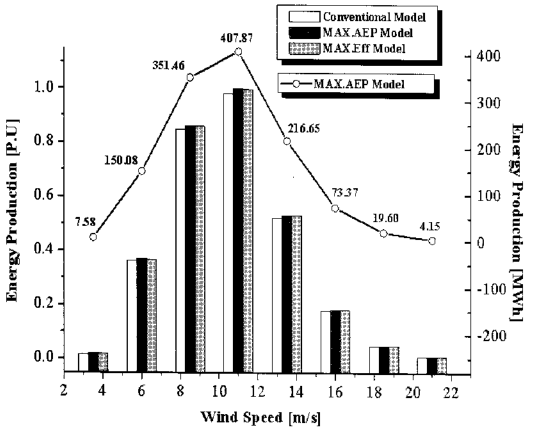


Fig. 10. Comparison results of energy production versus wind speed

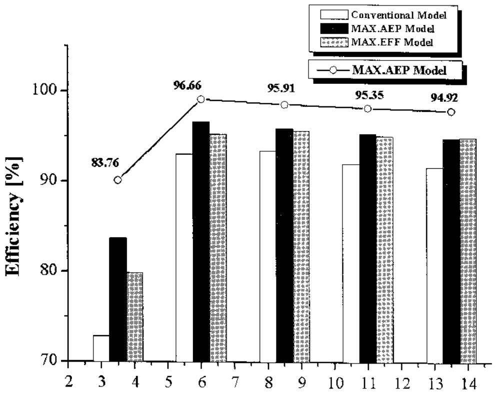
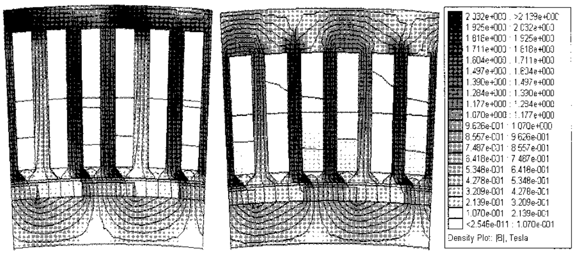


Fig. 11. Comparison results of efficiency versus wind speed

It is noted that the optimal design results of the AEP maximization model offers the best in both the generated power and energy production at every wind speed compared with the ones of the efficiency maximization model and the conventional model.

Likewise in Fig. 11, efficiency of the AEP maximization model is the best overall at every wind speed except at the rated speed, where the efficiency maximization model has been obtained. However, its difference is merely 0.1%. In addition, efficiency shows the highest at 6[m/s] near the average wind speed, which indicates the most frequent operating condition, even though it does not reach the peak power generation.



(a) Max. efficiency model (b) Max. AEP model

Fig. 12. Comparison results of the flux density distribution of the optimally designed SPMSG

In. Fig. 12, the flux density distribution of the optimally designed SPMSG for maximizing the efficiency and AEP are shown at the rated condition, which gives the distinctive difference in magnetic saturation at stator yoke because of the relatively larger x_3 (16%) of the optimal design results for maximizing the efficiency.

Considering the amount of energy production and efficiency at every wind speed provided in Figs. 10 and 11, the total AEP is obtained using (6) and compared in Table 2. Analogously to our expectation, maximizing the AEP model shows the best results in the total AEP by 1.3% to the maximizing efficiency model and by 3.4% to the conventional model, although it ranked second in efficiency by 0.1% at the rated condition.

Table 2. Comparison Results of Designed Models

	Design Variables				AEP [MWh]	Efficiency [%]
	X1 [mm]	X2 [mm]	X3 [mm]	X4 [mm]		
Model I	2.50	12.5	13.0	58.0	1193.4	91.6
Model II	1.948	10.5	22.3	69.2	1218.3	95.0
Model III	1.892	8.8	19.6	59.6	1234.5	94.9

(Model I: Conventional Model, Model II: Max. Efficiency Model, Model III: Max. AEP Model, Efficiency is compared at the rated condition)

It is generally understood that the wind generator should be evaluated with the total amount of energy production annually, whereby the optimal design of SPMSG maximizing the AEP is meaningful. Moreover, it is observed in the comparison results that the maximizing AEP model gives the best performance regardless of the wind speed, even in efficiency, compared with the other optimization results.

6. Conclusion

Optimal design of the direct-driven SPMSG for maximizing the AEP, using GA coupled with F.E.M, has been performed with the distributed parallel computing via internet web service. The parallel and internet distributed computing system is proposed for the stochastic real world optimization problem in which a FEA should be used for the evaluation of the objective function and the constraints. We showed that the FEA based optimization can be accelerated by a network of computers linked by the Internet. Furthermore, it is found that the AEP maximization is favorably effective as a design target of a wind generator in that the representative performance of a wind generator can be enhanced with AEP optimization significantly, compared with other optimization targets.

Acknowledgements

This work has been supported by KESRI(R-2007-2-060), which is funded by MOCIE(Ministry of commerce, industry and energy, and the Ministry of Education, Science Technology(MEST) and Korea Industrial Technology Foundation(KOTEF) through the Human Resource Training Project for Regional Innovation.

References

[1] Joseph J. F. Manwell, J. G. McGowan, A. L. Rogers, "Wind Energy Theory, Design and Application," *John Wiley & Sons*, 1st Ed., 2002.

[2] Yicheng Chen, Pragasen Pillay, Khan.A., "PM wind generator comparison of different topologies," *Proc. of 39th IAS Annual Meeting Conference*, Vol. 3, No. 3-7, pp. 1405-1412, October 2004.

[3] Khan M.A, Pillay, P. Malengret, "Impact of direct-drive WEC Systems on the design of a small PM wind generator," *Proc of IEEE Power Tech Conference*, Vol. 2, pp. 23-26, June 2003.

[4] Wang Fengxiang, Hou Qingming, Bo Jianlong, Pan Jian, "Study on Control System of Low Speed PM Generator Direct Driven by Wind Turbine," *Proc. of ICEMS2005*, Vol. 2, No. 27-29, pp. 1009-1012, September, 2005.

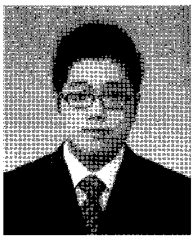
[5] Donald S.Zinger et al., "Annualized Wind Energy Improvement Using Variable Speeds," *IEEE Transactions on Industry Applications*, Vol. 33, pp. 1444-1447, November, 1997.

[6] H.S. Choi et al., "A Distributed Computing Technique for Analysis of Electric Machines Using Internet Web Services," *Digest of CEFC2004*, pp. 124, June 6-9, 2004.

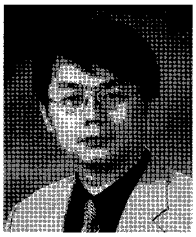
[7] A. Esoposito and L. Tarricone, "Grid Computing for Electromagnetics: A Beginner's Guide with Applications," *IEEE Antennas and Propagation Magazine*, Vol. 45, No. 2, pp. 91-99, April 2003.

[8] Chang-Eob Kim, "Optimum Design of a Linear Induction Motor Using Genetic Algorithm, Niching GA and Neural Network," *KIEE International Transactions on EMECS*, Vol. 3, no. 3, pp. 128-132, September 2003.

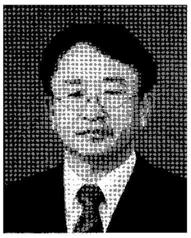
[9] Anders Grauers, "Design of Direct-driven Permanent-magnet Generators for Wind Turbines," Ph.D. Thesis Chalmers University, October 1996.



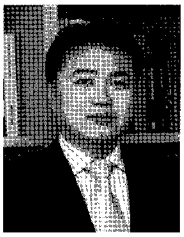
Hochang Jung
He was born in Busan, Korea on August 15, 1980. He received his B.S degree in Electronics Engineering from Dong-A University in 2007. He studies design and analysis of electric machines, and power equipment.



Cheol-Gyun Lee
He was born in Masan, Korea on January 28, 1967. He received his Ph.D degree in Electrical Engineering from Seoul National University in 1998. Currently, he is an Associate Professor at the School of Electrical Engineering, Dong-Eui University. He studies design and analysis of electric machines, and power equipment.



Sung-Chin Hahn
He was born in Seoul, Korea on June 27, 1955. He received his Ph.D degree in Electrical Engineering from Seoul National University in 1992. Currently, he is a Professor at the School of Electrical Engineering, Dong-A University. He studies the design and analysis of electric machines, power transformers, and power equipment.



Sang-Yong Jung
He was born in Masan, Korea on September 20, 1973. He received his Ph.D degree in Electrical Engineering from Seoul National University in 2003. Currently, he is Assistant Professor at the School of Electrical Engineering, Dong-A University. He studies the design and analysis of electric machines, and power equipment.