# Dynamic Magnetic Field Analysis for Small-sized Wind Power Generator

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**Abstract** To improve the efficiency of conventional power generators, product dissection was used to investigate design ideas. As design factors, the numbers of coils and magnets, the ratio of the coil and magnet numbers, the coiling method, and with or without a core in the coils were investigated. The result showed that the individual design factors were different; further, that it is difficult to ascertain similar design philosophies in dissected products.

Design and development of a small modular wind power generator was conducted based on the findings of the product dissection. The characteristics included rare-earth permanent magnets and core-less coil. To obtain the most suitable design method, dynamic magnetic field analysis was conducted. To confirm the results by analysis, a wind tunnel experiment was performed. The analytical results were within less than 10% error from those of the experimental results. The analysis is considered to be a tool for investigating the most suitable design for a generator. The wind power generator that was designed, developed, and manufactured is reported.

Keywords: Dynamic magnetic field analysis

## INTRODUCTION

Recent ecological and environmental trends that take sustainable and renewable energy such as solar-cell and wind power generation into consideration are becoming increasingly important. Large scale wind power generators have been installed, and by 2003 have reached a worldwide capacity of $3.9x10^7$ kW (mainly installed in Germany, the US, Spain, Denmark, and India), and $6.9x10^5$ kW in Japan[1]. At the same time, small-sized wind power generators for personal or small community use have been in demand. Since the history of power generator use is long, it can be said that their design ideas are fixed in place, and there should be a uniform design philosophy for obtaining maximum efficiency. However, while there are many papers on wind power generation systems (In 2004, projects in the areas of Greek, Arabia, Turkey, or islands are reported and one paper [2] reviews the state of the art), those for the generators themselves are few. Also reported are papers on turbine blades[3)-6)], statistical works, and control methods for maximum power tracking. Those papers on generators themselves seem to focus on large generators with Cu-Fe[7] and Nd-Fe-B[8] magnets.

From the literature survey, it was considered that more investigation into small-sized generators with Nd-Fe-B magnets was needed, and so this project started. To investigate the technology of small-sized power generators, product dissection was conducted using eight generators in the past research. The result of this product dissection showed that the individual design factors were different; and further, that it was hard to ascertain any similar design philosophy in the dissected products.

Power generation capability was estimated of starting with the study of disk-shape rotors with magnets in the outer periphery. However, the efficiency was not as good as was expected. Next, an axial gap type generator was investigated using rare-earth permanent magnets for both side faces and a core-less coil assembly. The idea of core-less coil allows for easy rotation in areas where not so strong winds predominate. Dynamic magnetic field analysis, which has not been actively conducted in the past, is considered of great importance for understanding the mechanisms of power generation. The preliminary analytical research resulted in the application of non-cored coils for wind power generators. A new wind power generator using Nd-Fe-B permanent magnets was designed, manufactured, and then dynamic magnetic field analysis and wind tunnel experiments were conducted. The results showed that the analysis could predict the experimental performance; and so could be a way to obtain more efficient generators in the future.

In this paper, the development of a small-sized power generator using dynamic magnetic field analysis and wind tunnel experiment is described.

## PRODUCT DEVELOPMENT OF WIND POWER GENERATOR

From studying the design philosophy of existing generators by product dissection, it was concluded that there is no unique rule for maximizing design efficiency. The design philosophy for wind power generator to be newly developed, therefore, was decided as follows.

1) Use rare-earth Nd-F-B permanent magnets; these are magnet
2) originally developed in Japan, and among the permanent magnets have the strongest power.
3) Removed the cores from the coils to eliminate the cogging torque in the generator.
4) Consider placing as many magnets and coils as possible in the size of generator. Design an adequate ratio of magnets and coils and space between magnets.
5) Design the generator as an axial-gap type with two faces of magnets (For a radial–gap type, past experiments did not show any better efficiency than from a commercial one.)

Finally the generator was designed and manufactured as shown in Figure 1.

Figure 1 Generator Assembly (Left) and Coil Assembly (Right)

## DYNAMIC MAGNETIC FIELD ANALYSIS

From the research by product dissection of existing generators, it was clarified that there was no rule for obtaining the most suitable design approach. This is because a dynamic magnetic field was not observed, even though the input and output of electrical information for generators had been experimentally implemented. To obtain the optimum design for a generator, it is necessary to understand the dynamic magnetic field in a generator.

The dynamic magnetic field was analyzed by ELF/MAGIC software especially made for analyzing a dynamic magnetic field. The Integral Element Method was used combined with surface magnetization and magnetic moment. The pre and post processor used was FEMAP Ver. 8.1. A DELL PRECISION 340 PC with a 2.2 GHz Pentium 4 and 1GB memory was used. Around 2,000 nodes were used for the analysis, with an element number around 1,500. Time for calculation was about 5-7 days in each case. The model of the generator, 450 mm diameter, was three dimensional consisting of a magnet, coil and a back yoke. An axi-symmetric model of 45 degrees phase was applied. Figure 2 shows the generator assembly, and Figure 3

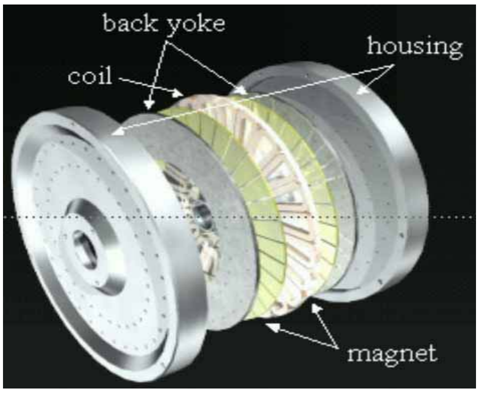


Figure 2 Generator Assembly (Computer Graphics)

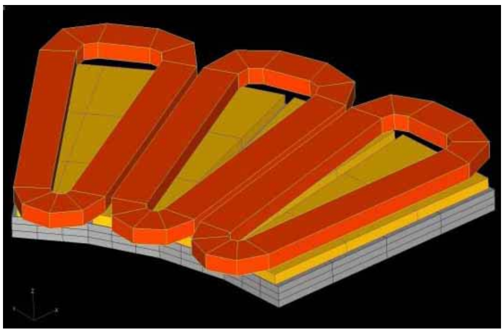

Figure 3 Analytical Model

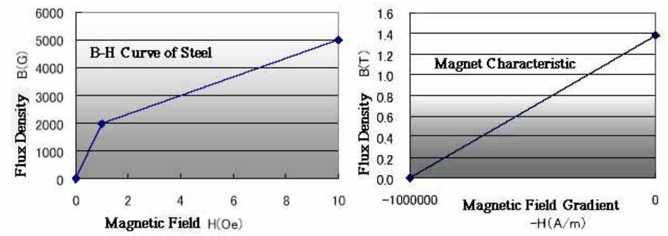


Figure 4 Magnetic Material Characteristics Used in the Analysis

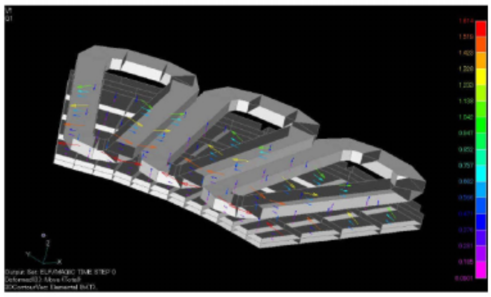

Figure 5 Example of Analytical Magnetic Field Result (Vector Diagram)

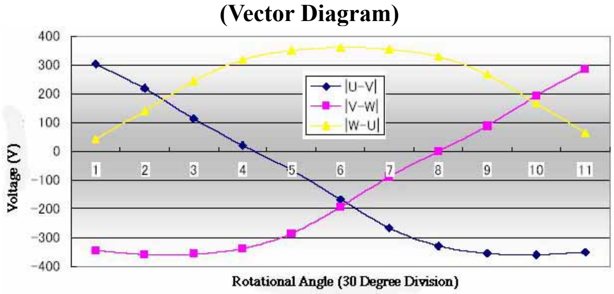


Figure 6 Voltage in Three Phase Wire

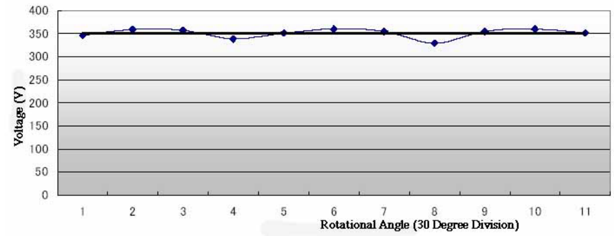


Figure 7 Voltage after Rectification

the model for the analysis. The generator used for the calculation rotates at 300 rpm. The material characteristics used for the analysis are shown in Figure 4. One example of an obtained result is shown in Figure 5, shown as a vector expression. For clarity, the voltage in the three phase wire (Y wire binding) is shown in Figure 6. When the current is rectified, the voltage is as shown in Figure 7; while the average voltage is 350 V at a rotational velocity of 300 rpm.

## WIND TUNNEL EXPERIMENT

Wind tunnel experiments were conducted in a Maeda

**Figure 8 Wind Tunnel Apparatus**

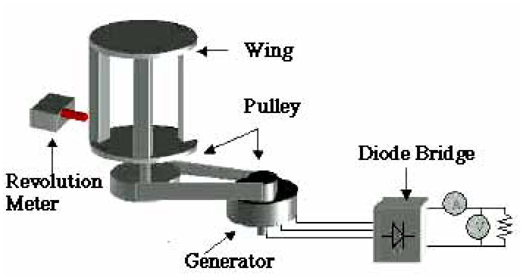


**Figure 9 Illustration of Test Set-up**

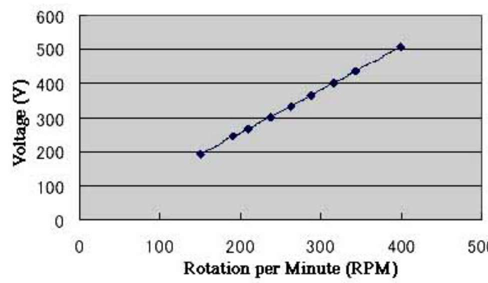


**Figure 10 Relation Between Output Voltage and Rotation per Minutes**

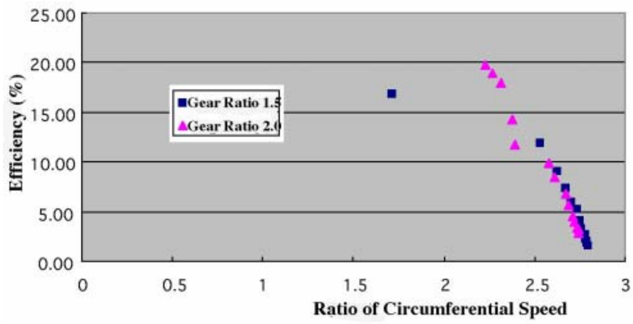


**Figure 11 Experimentally Obtained Efficiency**

Corporation facility located in Nerima, Tokyo, to evaluate the power generated by the developed generator. The wind tunnel specification for the experiment was 4.3 m x 3.0 m cross-sectional area, length for measurement 8 m, and wind velocity 0. 5 – 8.0 m/s. In the apparatus, three gyro-type wings of 1,700 mm diameter and 1,700 mm height were installed as shown in Figure 8. The pulley prepared as shown in Figure 9 produced the rotation acceleration; the ratio was set at three stages (ratios of 1.5, 2.0, and 3.0). The 450 mm diameter generator was used in the experiment. The three-phase alternating current from the generator was rectified through a diode bridge, and voltage, current, and power were monitored by voltage, current, and digital watt meters. There were two test items; the first being the static characteristic of the relation between rotation and voltage with or without electrical loads, the second, the start-up characteristic when an outside resistance was attached.

The voltage versus rotation per minute was obtained, and is shown in Figure 10. The voltage at the 300 rpm rotation was found to be 380 V, which is slightly higher than the analytically obtained value of 350 V. The difference is within 10% error, and so the method for an analytically obtained dynamic magnetic field was found to be useful for designing and optimizing power generator from various configurations.

Figure 11 shows the efficiency of the electric power generated, an efficiency of about 20%, which is considered to be relatively high, can be obtained in the case of a gear ratio of 2.0.

## DISCUSSION

### Design Philosophy and Efficiency of Wind Power Generators

Most wind power generators work at a comparatively high wind velocities, such as more than 10m/s. However, in community areas where people live, wind velocities are not high enough to produce electricity from a wind power generator. As the field measurements conducted using a conventional small-sized wind power generator show, the efficiency of a wind power generator is not high due to the weak wind environment around the areas used for the experiments. To obtain a relatively higher power generation in an area with a weak wind environment, a more efficient wind power generator is desirable. To obtain such a wind power generator, it was necessary to study the design philosophy of existing wind power generators. The result in the previous research on the product dissection indicated that no unified or standardized design philosophy existed. This result was considered due to the past design methods were mainly based on experience or experiment. The dynamic magnetic field, which is of the most important factor in generator design, has yet to be clarified.

### Magnetic Field Analysis for the Generator with Rare-earth Permanent Magnets and Coreless Coils

The one of the authors developed the Eddy Current Brake[8] (ECB retarder) for trucks and buses. The rotational part of the ECB, called a drum, produces a Lorentz force when the Nd-Fe-B permanent magnet approaches the drum, and the magnetic field penetrates into the rotational part. The Lorentz force can then act as a braking (retarding) force. For endurance and strength, the material of the drum is steel. The effect of the material on the braking force was studied when the ECB was being development. Figure 12 shows the effect of material permeability on the braking force. In Figure 12, S is the velocity parameter, and $F_3$ the braking force. The figure shows that a drum material of lower permeability gives a higher braking force in the low velocity range. This result suggests that for a wind power generator a core material of low permeability (aluminum or air for instance) might produce more current in the coils. The reason why the braking force is high with a low permeability material is considered due to the way the magnetic field penetrates into the drum. Figure 13 shows FEM analysis of the magnetic field where the drum material is steel. As is

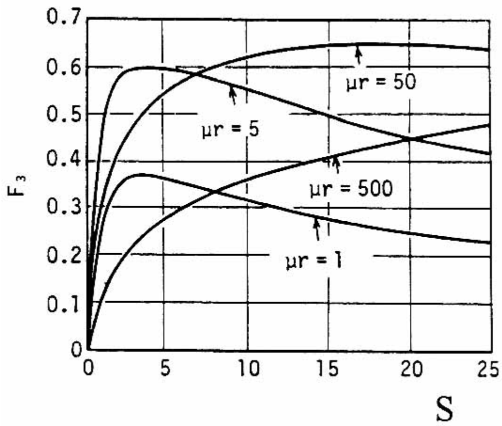


**Figure 12 Effect of Permeability on Braking Force for Rotational Velocity**

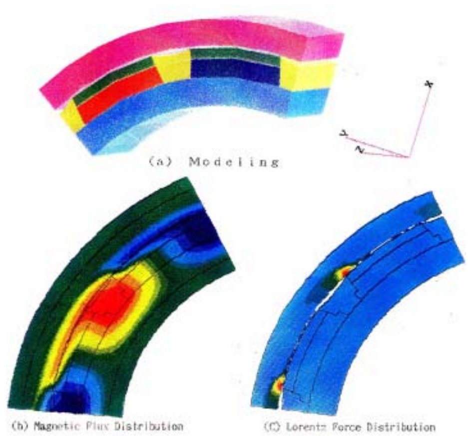


**Figure 13 Magnetic Field and Lorentz Force Distribution**

apparent, the magnetic field penetration in the drum is dragged in a rotational direction rather than penetrating into the drum in a radial direction. However, for a wind power generator, more analytical work will be required.

**CONCLUDING REMARKS**

To obtain an efficient wild power generator, design and manufacture has been conducted from the viewpoint of dynamic magnetic field analysis and wind tunnel testing to study generator design ideas. The results obtained can be summarized as follows.

1. The dynamic magnetic field was obtained with special software utilizing the Integrated Element Method, and the result well fits, within the error of 10%, the result from wind tunnel experimentation. The analytical method used here can assist approaches to obtain optimum designs for future power generators.
2. The use of dynamic magnetic field analysis is desirable to realize generators designed for optimum power efficiency, especially small-sized wind power generators for use in areas with a low wind velocity conditions.

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