PROPOSAL OF UNIQUE WIND POWER UNIT.

By

Ahmed Mohamed Galal Abdel Moneim Mohamed

Supervised by / Professor Toshiaki Kanemoto

Faculty of Graduate School of Engineering,

Kyushu Institute of Technology, Japan.

Doctor of Philosophy

In

Mechanical Engineering

March - 2009

Table of Contents

Nomenclatures

Term	Stand for
a	Axial induction factor
a'	Tangential induction factor
c	Chord length
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Rotational torque coefficient [$=T/(\rho AV^2 d_F/4$]
C_P	Output coefficient [$=P/(\rho AV^3/2)$]
D	Rotor diameter ratio[=(rear diameter)/(front diameter)]
d	Wind rotor diameter
E	Generator induced voltage
F_D	Drag force
F_L	Lift force
F_N	Thrust force
F_T	Tangential force
f	Frequency
I	Generator induced electric current
L	Dimensionless axial distance between wind rotors [$=l/d_F$,]
l	Distance between tandem wind rotors
MEL012	Wind rotor blade profile
N	Wind rotor rotational speed
N_{GF}	Rotational speed of inner armature
N_{GR}	Rotational speed of outer armature

N_S	Synchronous speed
R	Dimensionless rotor radius
r	Rotor radius
p	Number of poles
P	Output power
P_a	Maximum extracted output from wind
P_r	Wind pressures
P_r^+	Wind pressures at positions (2)
P_r^-	Wind pressures at positions (3)
P_0	Net output power
Q	Volume flow rate
R_{emax}	The maximum Reynolds number
r_{Hub}	Radius at the hub
r_{Tip}	Radius at the tip
S	Slip[= $(N_S - N_T)/ N_S$]
T	Rotational torque
T_{GF}	Rotational torques of inner armature
T_{GR}	Rotational torques of outer armature
u	Rotational velocity[$=\omega r,\ \omega=2\pi N/60$]
V	Wind velocity
v_{23}	Wind velocity at both positions (2), and (3)
v_4	Downstream wind velocity at position (4)
W	Relative speed
Z	Blade number
α	Attack angle

β	Blade setting angle
ε	Lift to drag ratio
ϕ_{in}	Blade inlet angle
ϕ_{out}	Blade outlet angle
η	Generator efficiency
λ	Tip speed ratio
ρ	Air density
ψ	Blade twist angle

< Subscripts >	Stand for
BEP	Best efficiency point
F	Front wind rotor
G	Generator
opt	Optimal
R	Rear wind rotor
r	Local (at radius r)
T	Relative
1	Output
2	Input
rotor	Wind rotor

Chapter 1

Introduction

Wind power is a significant promising source of renewable energy that will play a very important role in the 21st century. As wind turbines are very effective to generate the electrical energy from wind power. There is a great need/obligation to exploit the renewable energy because of the rapid decrease of the earth's fossil energy sources, and the global warming resulting from utilizing them. Wind exists everywhere on Earth, and in some places with considerable energy density. Wind power was widely used in the past, for mechanical power as well as transportation. Certainly, it can be utilized effectively for generating the electrical power because it is a sustainable, home grown and clean source of power.

Wind turbines can either operate at fixed speed or variable speed. For a fixed-speed wind turbine, the generator is directly connected to the electrical grid. Whereas in a variable speed wind turbine, the generator is controlled by power electronic equipment. Different research has been conducted on how to optimize the behavior of wind power units. Some researches concentrated mainly on the simulation of the performance of the horizontal wind turbine of single rotors using commercial software. Others made a comparison between theoretical and experimental work in the field. Some other research focused on tandem wind rotor blades, and their results showed higher performance than single wind rotors. All these previous attempts used either gearboxes, or pitch control mechanisms, or even both, which is different from the concept used in this research.

The author introduces a new/unique technological development in the field of wind turbines, through a vision of a new design of intelligent wind turbine generators that may make a revolution in the field of the wind power unit industry. This work proposes a propeller type horizontal axis wind power unit with tandem wind rotors. The front and the rear wind rotors drive the inner and the outer armatures of the generator whereas the rotational speeds of the tandem wind rotors are adjusted in cooperation with the two armatures of the generator in response to the wind speed. It was verified experimentally that the output was increased and kept constant at the rated operation of the unique wind power unit without using either gearboxes, or pitch control mechanisms.

1.1 Importance of Renewable Energy

The modern life style depends tremendously on the use and existence of fossil fuels, such as oil, gas, and coal, as shown in Fig. 1-1. With levels of these fuels constantly decreasing, it is important to become less dependent on fossil fuels and more dependent on renewable energy sources. The decreasing levels of fossil fuels are not the only reason to begin using renewable energy, but also pollution has become a huge problem in many countries around the world, especially in the developing world. With the increase of carbon emissions, air quality can be very low in some areas, and this can lead to respiratory diseases and cancer. The main reason to switch to cleaner energy

Oil (1)

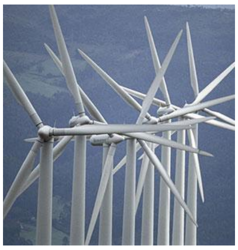
Gas (2)

Nuclear (3)

Coal (4)

Fig 1-1 Fossil energy resources

production methods is the global warming aspect due to the solar insolation, and green house effects [5] [6] [7]. The more carbon dioxide pumped into the atmosphere has a dangerous effect. It is possible to slow down and dilute the effects of global warming through the wide spread use of renewable energy resources [8][9]. Renewable energy is proving to be commercially viable for a growing list of consumers and uses as it offers our planet a chance to reduce carbon emissions, clean the air, and put socities on a more sustainable footing. It also offers countries around the world the chance to improve their energy security and spur economic development. Renewable energy sources such as shown in Fig. 1-2, can meet many times the present world energy demand, so their potential is enormous [15][16]. They can enhance diversity in energy supply markets, secure long-term sustainable energy supplies, and reduce local and

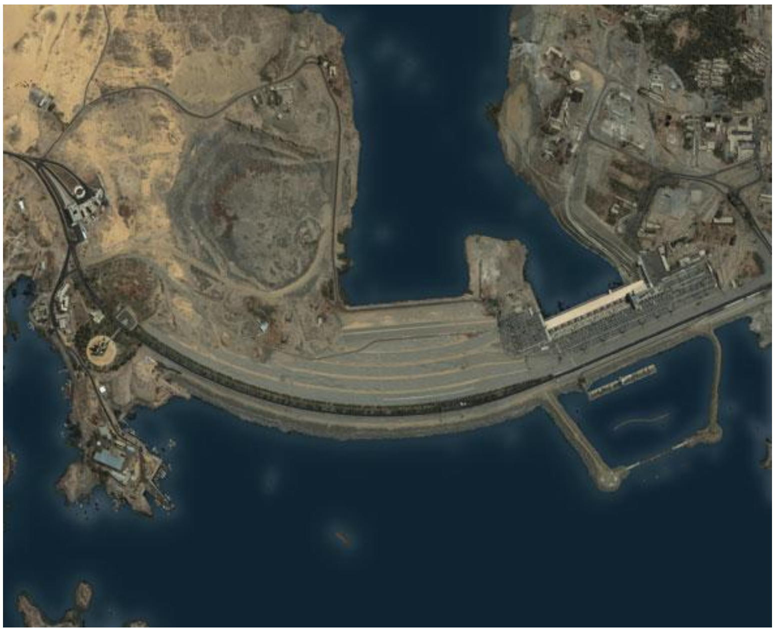


Wind [10]

Solar [11]

Geothermal [12]

Wave [13]



Hydropower, Aswan dams-Egypt [14]

Fig 1-2 Renewable energy resources

global atmospheric emissions.

Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and bio-fuels and hydrogen derived from renewable resources [17][18][19]. One of the important examples of exploiting the hydropower energy is the dams built on River Nile in Egypt [20]. Two dams straddle the river at this point: the newer Aswan High Dam, and the older Aswan Dam or Aswan Low Dam, as shown in Fig. 1-2. The aim of this water project was to prevent the river's flooding, generate electricity and provide water for agriculture. Without impoundment, the River Nile would flood each year during summer, as waters from East Africa flowed down the river as they did in ancient times. These floods brought nutrients and minerals that made the soil around the Nile fertile and ideal for farming. As the population along the river grew, there came a need to control the flood waters to protect and support farmland and cotton fields. In a high-water year, the whole crop may be entirely wiped out, while in a low-water year there was widespread drought and famine. Egypt depends on Aswan Dams as a main clean and renewable source of

Fig. 1-3 Typhoon striking coasts of Japan [21]

electric power.

1.2 Wind Energy

Wind power technology is one of the most promising technologies for electricity generation. Winds can vary in strength, from the lightest breeze to the terrifying power of hurricane or tornado. In Japan, high and strong wind is called “typhoon”, which hits the islands at the mid-autumn, mostly in September, such as shown in Fig. 1-4. In America, these strong winds are called hurricane. A hurricane is a wind blowing faster than 118 km per hour [22]. Wind energy is one of the most promising alternatives to fossil and nuclear fuels. It can supply power at remote places where electrical grid cannot reach. Advanced technologies in the field of electronics, and long experience in the work of wind turbines, made the market of wind power units far better than before because of the fruitful advantages. Wind energy is estimated to be able to supply at least twenty percent of world renewable energy needs in the near future. Wind power is utilized in many countries around the world, especially at northern part of Europe, USA, and some parts of Asia, like Japan, and other parts in Africa, such as Egypt. Day by day number of wind power units is increasing all over the world.

1.2.1 Wind power utilization in Japan

At the end of 2007, the total wind power capacity in Japan was 1,538 MW (1,331 turbine units) for an annual net increase of 229 MW. Compared with EU countries, Japan is very isolated, and so the influence of wind generation on grid stability is considered very large, regardless of how small the penetration ratio is. Moving to offshore installations has not yet begun due to deep-water conditions, but a national investigation was initiated in 2007 [23]. The Japanese government introduced a Renewable Portfolio Standard (RPS) law in April 2003 with the aim of stimulating renewable energy to provide 1.35 per cent of total electricity supply in 2010. The leading regions for wind power development in Japan are Tohoku and Hokkaido in the north of the country, with an installed capacity respectively of 275 and 159 MW, and Kyushu in the south, with 113 MW, as shown in Fig. 1-4. Japanese turbine

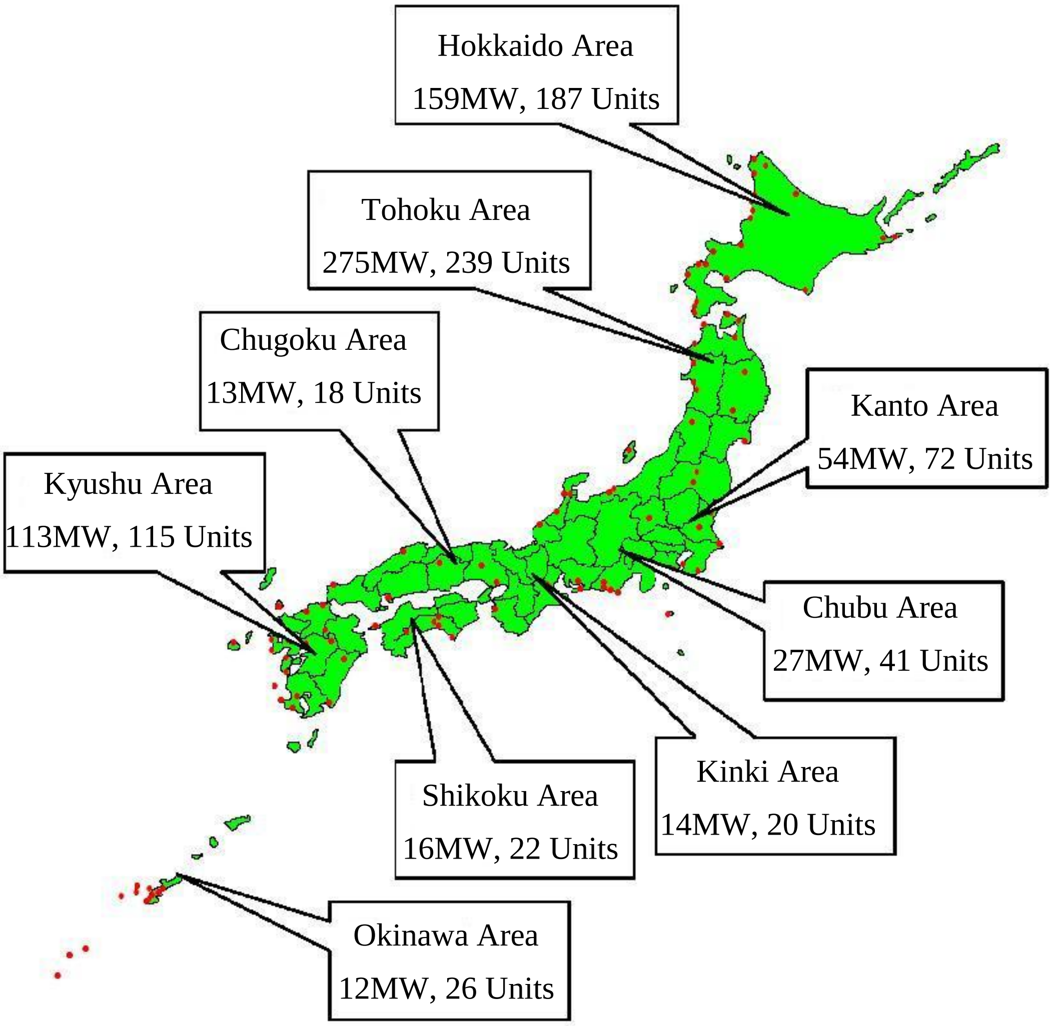


Fig. 1.4 Japan wind turbine locations, and its power productions [24]

manufacturer Mitsubishi took about a third of the supply market in 2004, the remainder being serviced by European companies [15]. Two issues have created challenges for Japanese wind developers. Firstly, the country is relatively densely populated in areas where construction is feasible, and secondly, some of the terrain is complex, with the added risk of typhoons. Both the Japanese Wind Energy Association and the Japanese Wind Power Association have therefore been supporting further R&D activity in the areas of grid stability, technical safety, lightning protection and generation output prediction. Partly as a result of these issues, serious consideration is being given to offshore development round Japan's coastline, although this is limited by available water depth.

1.2.2 Wind power utilization in Egypt:

Egypt had made much effort to step up the use of renewable energy, such as the broad project for winning wind energy. A national strategy for wind energy was put in place as early as 1988 with the plan to have 6000 MW wind farms by the year 2017. The production aim is 21 billion kWh saving 4.68 Million tons of oil equivalent. The Ministry of Electricity & Energy of Egypt has embarked on this wind energy program to utilize the promising areas, especially the west shore of the Gulf of Suez where wind speed reaches 10 meters per second being one of the best locations worldwide. Other promising areas include East Oinat where the wind speed reaches 7 meters per second, and the north coast reaching 6.5 meters per second. The best site was selected at Zafaraana on the Red Sea, as shown in Fig. 1-5, where it was planned to have over 6000 MW wind farms [16][17]. Egypt accomplished a significant achievement in electric generation from wind energy. A wind farm at Zafarana of 63 MW connected to national grid in 2001 as shown in Fig. 1-8. There are also potential projects increased the installed to capacity to 100 MW in 2004. It is targeted to have total installed capacity of 600 MW by the year 2010.

1.3 Wind Power Units

People have harnessed the wind force peacefully, and its most important usage probably was the propulsion of ships using sails before the invention of the steam engine and the

(a) Site of Zafarana wind park [25]

(b) Zafarana wind power units [25]

Fig. 1-5 Zafarana wind park, Egypt

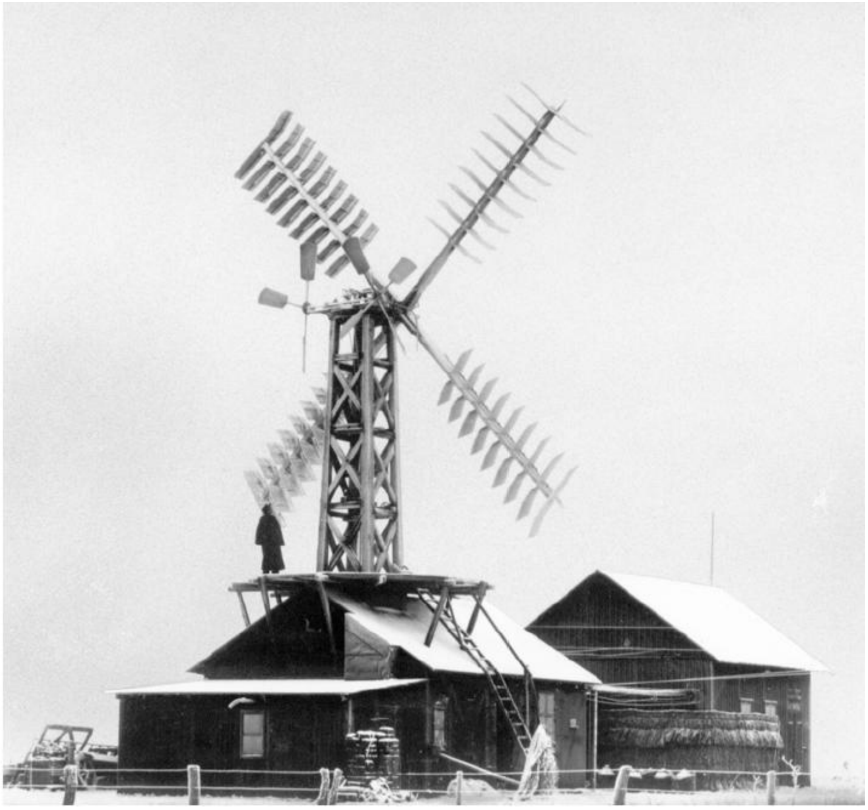


Fig. 1.6 Poul La Cour windmill [13]

internal combustion engine. Wind has also been used in windmills to grind grain or to pump water for irrigation or, as in some parts of Europe, to prevent the ocean from flooding low-lying land. At the beginning of the twentieth century electricity came into use and windmills gradually became wind turbines as the rotor was connected to an electric generator. The first electrical grids consisted of low-voltage DC cables with high losses. Electricity, therefore, had to be generated close to the site of use. On farms, small wind turbines were ideal for this purpose and in Denmark Poul La Cour, who was among the first to connect a windmill to a generator, as shown in Fig. 1-6 [26]. An example of La Cour's great foresight was that he installed in his school one of the first wind tunnels in the world in order to investigate rotor aerodynamics. Gradually, however, diesel engines and steam turbines took over the production of electricity and only during the two world wars, when the supply of fuel was scarce, did wind power flourish again. However, even after the Second World War, the development of more efficient wind turbines was still pursued in several countries such as Germany, the US, France, the UK and Denmark.

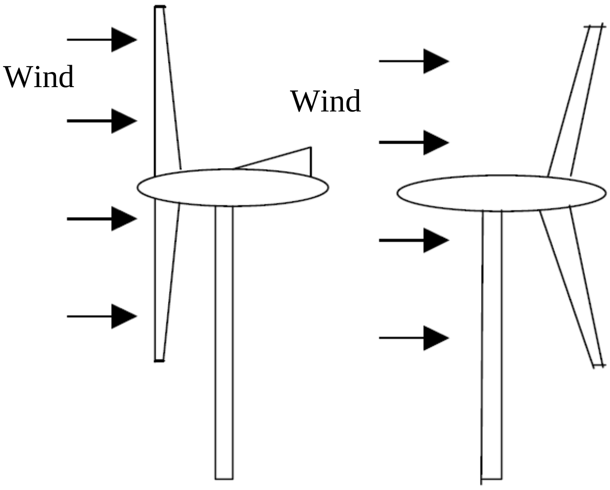
In the mid 1950s Juul introduced what was later called the Danish concept by constructing the famous Gedser turbine, which had an upwind three-bladed, stall regulated rotor, connected to an AC asynchronous generator running with almost constant speed(18). With the oil crisis in 1973, wind turbines suddenly became interesting again for many countries that wanted to be less dependent on oil imports; many national research programs were initiated to investigate the possibilities of utilizing wind energy. Large non-commercial prototypes were built to evaluate the economics of wind produced electricity and to measure the loads on big wind turbines. Since the oil crisis, commercial wind turbines have gradually become an important industry with an annual turnover in the 1990s of more than a billion US dollars per year. Since then this figure has increased by approximately 20 per cent a year.

1.3.1 Types of wind turbines:

Wind turbines are mechanical devices specifically designed to convert part of the kinetic energy of the wind into useful mechanical energy. Several designs have been devised throughout the times (27)(28). Most of them comprise a rotor that turns round propelled by lift or drag forces, which result from its interaction with the wind. Depending on the position of the rotor axis, wind turbines are classified into vertical-axis and horizontal-axis ones, as shown in Fig. 1-7 (29). Most successful vertical-axis wind turbine is the Darrieus rotor. The most attractive feature of this type of turbine is that the generator and transmission devices are located at ground level. Additionally, they are able to capture the wind from any direction without the need to yaw. However, these advantages are counteracted by a reduced energy capture since the rotor intercepts winds having less energy. Furthermore, despite having the generator and transmission at ground level, maintenance is not simple since it usually requires rotor removal. In addition, these rotors are supported by guy-ropes taking up large land extensions. By these reasons, the use of vertical-axis wind turbines has considerably declined during the last decades. Nowadays, almost all commercial wind turbines connected to grid have horizontal-axis two-bladed or three-bladed rotors. The rotor is located at the top of a tower where the winds have more energy and are less turbulent. The tower also holds up a nacelle. The gearbox and the generator are assembled inside. There is also a yaw mechanism that turns the rotor and nacelle. In

Horizontal Axis [30] Vertical Axis [31]

Fig. 1-7 Wind turbines types according to rotational axis



Upwind Downwind

Fig. 1-8 Wind turbines types according to wind direction [32]

normal operation, the rotor is yawed to face the wind in order to capture as much energy as possible. Although it may be very simple in low power applications, the yaw system is likely one of the more complicated devices in high power wind turbines. Finally, the power electronics are arranged at ground level.

Horizontal-axis wind turbine units can be classified also as downwind or upwind types according to the direction of wind facing the wind power unit, as shown in Fig. 1-8 [32]. Downwind machines have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, however, since cables are needed to lead the current away from the generator. A more important advantage is that the rotor may be made more flexible. This is an advantage both in regard to weight and the structural dynamics of the machine, i.e. the blades will bend at high wind speeds, thus taking part of the load off the tower. The basic advantage of the downwind machine is thus, that it may be built somewhat lighter than an upwind machine. The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine than with an upwind design.On the other hand, the basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design. On the other hand, there is also some wind

a) Near-shore wind farm [33].

b) Europe's largest onshore wind farm in Scotland [34].

c) World's largest offshore wind farm in Denmark [35]

d) Author at world's largest onshore wind farm of Altamont pass, California, USA

Fig. 1-9 Different types of wind farms

shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The basic drawback of upwind designs is that the rotor needs to be made rather inflexible, and placed at some distance from the tower (as some manufacturers have found out to their cost). In addition, an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

Unless it is a single wind turbine for a particular site, such as an off-grid home in the country, most often when a good wind site has been found it makes sense to install a large number of wind turbines in what is often called a wind farm or a wind park. Obvious advantages result from clustering wind turbines together at a windy site. Reduced site development costs, simplified connections to transmission lines, and more centralized access for operation and maintenance, all are important considerations. Wind farms are divided into main three types: onshore, nearshore, and offshore as shown in Fig. 1-9. Onshore wind farm installations are in hilly or mountainous regions which tend to be on ridgelines generally three kilometers or more inland from the nearest shoreline. Nearshore wind farm installations are on land within three kilometers of a shoreline or on water within ten kilometers of land, while offshore wind farms are generally considered to be ten kilometers or more from land.

1.4 Previous Work on Wind Power Units:

Wind turbines can either operate at fixed speed or variable speed. For a fixed-speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power (21).

Different research has been done to study and to optimize the behavior of wind power units. Some research concentrated mainly on simulation of the performance of the horizontal wind turbine using single rotors using commercial software. Others made comparison between theoretical and experimental work in the field. Some other research was based on experiments using tandem wind rotor blades, and their results showed higher performance than single rotors. Methodologies were developed to estimate the chord distribution airfoil and blade twist along the radius of the blade by using axial and angular moment conservation equations, blade element theory and optimization processes [(36)(32)].

1.4.1 Doubly fed induction generators

Most of the major wind turbine manufactures are developing new larger wind turbines in the 3-to-6-MW range [(37)]. These large wind turbines are all based on variable-speed operation with pitch control using a direct-driven synchronous generator (without gear box) or a doubly-fed induction generator. Fixed-speed induction generators with stall control are regarded as unfeasible for these large wind turbines. Nowadays, variable-slip, i.e., the slip of the induction machine is controlled with external rotor resistances, or doubly-fed induction generators are most commonly used by the wind turbine industry for larger wind turbines. The major advantage of the doubly-fed induction generator, which has made it popular, is that the power electronic equipment only has to handle a fraction (20-30 %) of the total system power [(38)]. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator, apart from the cost saving of using a smaller converter.

According to Carlson et al. the energy production can be increased by 2-6 % for a variable-speed wind turbine in comparison to a fixed-speed wind turbine [(39)]. Zinger et al. stated that the increase in energy can be 39 % [(40)]. Mutschler et al. has shown that the gain in energy generation of the variable-speed wind turbine compared to the most simple fixed-speed wind turbine can vary between 3-28 % depending on the site conditions and design parameters [(41)]. Calculations of the energy efficiency of the doubly-fed induction generator system, has been presented before [(42)]. Datta et al. have made a comparison of the energy capture for different schemes of the electrical configuration, i.e., fixed-speed wind turbine using an induction generator, full variable-speed wind turbine using an inverter-fed induction generator, and a variable-speed wind turbine using a doubly-fed induction generator. According to his research, the energy capture can be significantly enhanced by using a doubly-fed induction machine as a generator and the increased energy capture of a doubly-fed induction generator by over 20 % with respect to a variable-speed system using a cage rotor induction machine and by over 60 % in comparison to a fixed-speed system (43). Aspects such as the wind distribution, electrical and mechanical losses of the systems were neglected in that study. Control of the doubly-fed induction machine is more complicated than the control of a standard induction machine and has all the limitations that the line-fed synchronous generator has, e.g., starting problem, synchronization and oscillatory transients. Wang et al. found through simulations that the flux is influenced both by load changes and stator power supply variations (44). The flux response is a damped oscillation and the flux and rotor current oscillate more severely when the speed is increasing compared to when the speed is decreasing. Heller et al. have investigated the stability of the doubly-fed induction machine mathematically. They have shown that the dynamics of the doubly-fed induction machine have poorly damped eigenvalues with a corresponding natural frequency near the line frequency and that the system is unstable for certain operation conditions (45).

1.4.2 Single rotor wind turbines

The design of wind energy conversions systems is a difficult task because it must take into account many complex design aspects (46). Varol et al. studied the aspect of the correct position of the aerofoil with regard to the wind direction (47). Wind power and the impact of wind power technology both on energy markets and on electric system stability become necessary to be flexible so that to allow predicting energy output (48)(49)(50). The results of models should provide elements for preliminary blade turbine design and for evaluating the extracted wind power.

A methodology was developed by Mejia et al. to estimate the chord distribution airfoil and blade twist along the radius of the blade by using axial and angular moment conservation equations, blade element theory and optimization processes. This methodology took into account the concept related with getting wind power for different chord blade values and selecting one that facilitates to get the maximum value for wind power.

Simulation of power generation output was carried out by using a wind-speed probability distribution function obtained from data collected at the Guajira region of Colombia [51]. Experiments were done together with simulation using airfoil NACA 63–420, using 3 bladed single wind rotor of a radius of 30m at a rated wind velocity

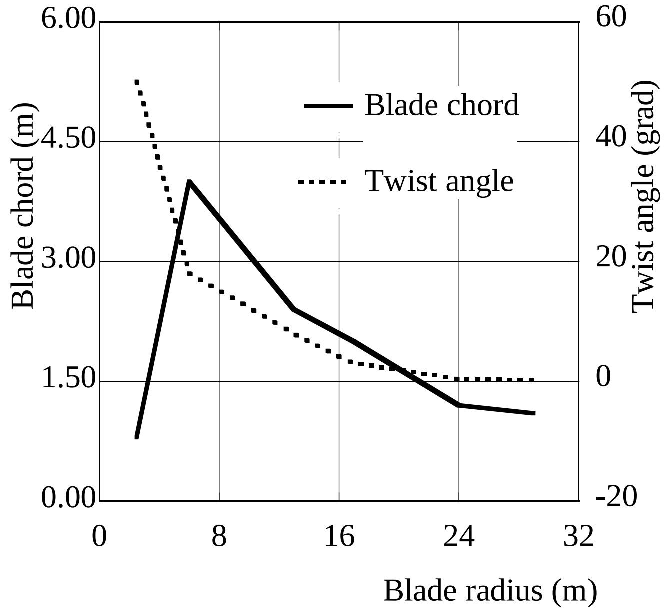


Fig. 1-10 Chord blade distribution and attack angle along the blade radius [51].

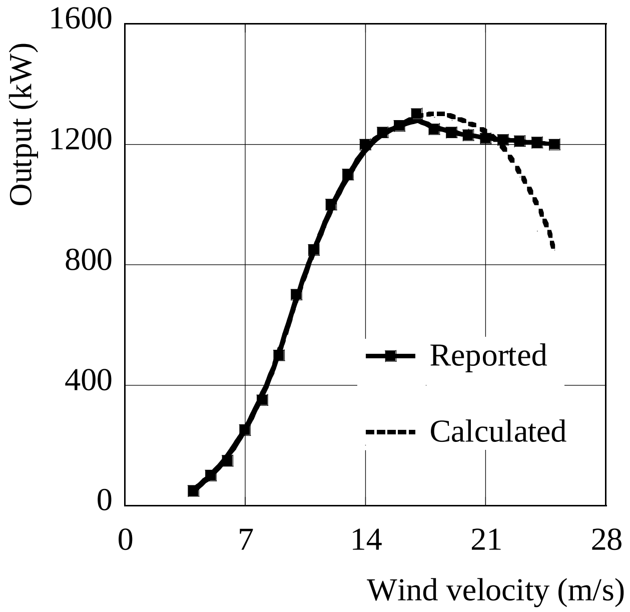


Fig. 1-11 Comparison between theoretical and experimental output values [51]

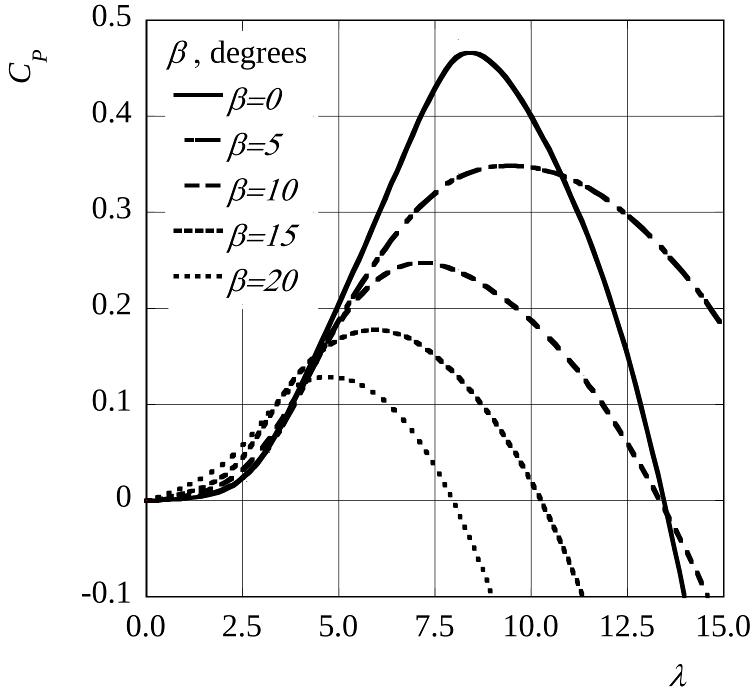


Fig. 1-12 Output coefficient against tip speed ratio (53)

15m/s. Blade twist and chord distribution was simulated as shown in Fig. 1-10. Power curve simulated was compared with experiments as shown in Fig. 1-11. Through these figures, a decrease of the chord blade in order to guarantee better lift and power generation can be achieved. Likewise, the twist angle helps with the purpose of having a maximum aerodynamic efficiency along the blade. It is observed that the theoretical results are in agreement to experimental results until reach the wind speed of 17 m/s.

Maximum output control of wind turbine and induction generator connected with two back to back voltage source converters to grid were studied by Bana Sharifian et al. (52). The currents were controlled by indirect vector control method. Output coefficient C_P was expressed as a function of tip speed ratio λ, and the blade setting angle β. Simulations showed that the value of maximum C_P was 0.48 at β=0 degrees, and λ=8 as shown in Fig. 1-12.

1.4.3 Tandem rotors wind turbines

The idea of tandem wind rotors is that using two sets of blades instead of one to increase the output. Previous attempts were done using this idea because when a traditional wind turbine with a single rotor system is used for energy conversion, only a part of the available energy in the wind is exploited. Further energy can be extracted by installing a second rotor in the wake. At the same time, the maximum energy that

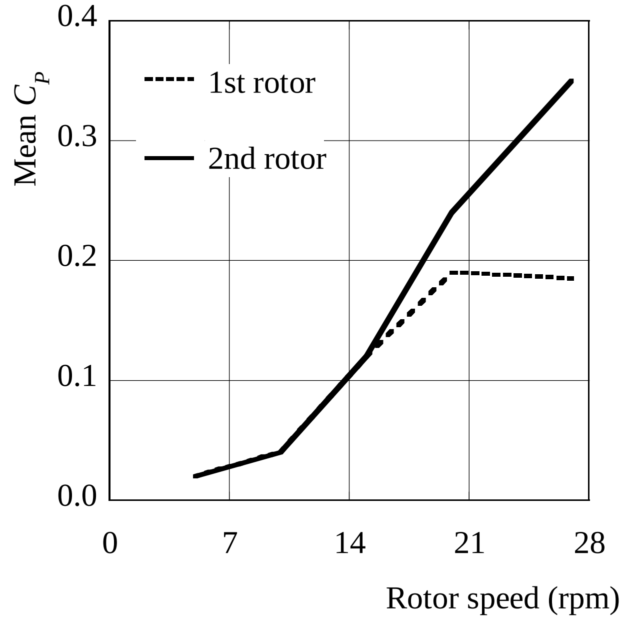


Fig. 1-13 Output against rotor rotational speed [52]

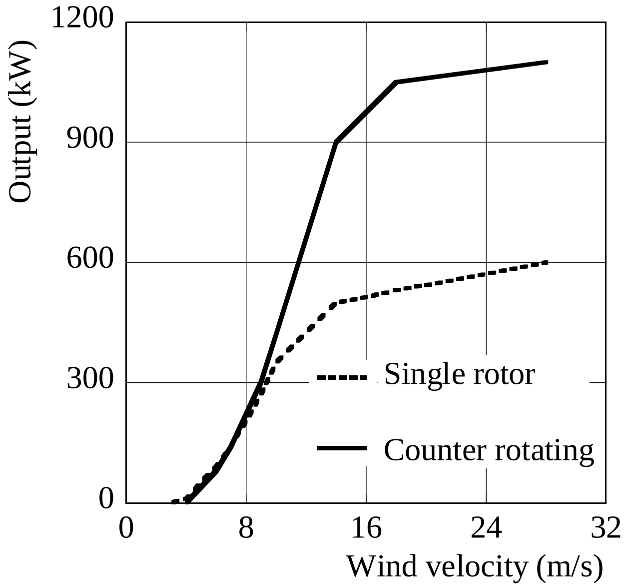


Fig. 1-14 Comparison between output of single and counter rotating rotors [52]

can be extracted by two rotors of same diameters is increased from 59% to 64% of the available energy that is the Betz limit for two rotors [(21)]. A counter-rotating wind turbine system was proposed by W.Z. Shen [(53)]. This system consisted of two 3-bladed rotors of equal diameter of 20.5m and separated by an appropriate distance. One of the rotors was rotating in counter-clockwise direction while the other in clockwise direction. The performance of the model was simulated using Navier-Stokes code EllipSys3D. Figure 1-13 shows the simulated output of the two rotors at wind velocity V=10m/s through different rotational speeds, while Fig. 1-14 shows simulated output at different wind velocities. It is shown from these figures that the second wind rotor can achieve reasonable output which can increase the efficiency of the wind power unit.

In 2002, Appa Technology Initiatives has built a prototype in California and performed some field tests on his prototype model that consisted of a 6 KW counter-rotating wind turbine system with two 2-bladed rotors of 4m diameter, and tip speed ratio λ=6, while using a gear box, and a mechanical efficiency=.8 [(54)]. The results of these tests indicated that a contra-rotating turbine system could extract additional 30% power from the same wind stream.

In 2005, Jung et al. has considered experimentally and numerically (using the quasi-steady strip theory) a 30 kW CRWT that are consisted of an upwind auxiliary rotor of 5.5m and a downwind main rotor of 11m. The prototype of tandem wind rotors with a gearbox is shown in Fig. 1-15 [(55)]. For a counter rotating wind turbine where two rotors are rotating in opposite directions, the flow is usually unsteady.
Despite the fact that this data was spread out in different areas, a fairly good correlation between the test data and analysis results is noticed. The results of the experiments indicate that the current counter rotating system is very effective in extracting energy from the wind: the maximum C_P reaches as high as 0.5.

Professor Ushiyama, from Japan proposed two kinds of two staged wind turbines consist of the co-axial type and the counter-rotating type [(56)]. The co-axial-type is used to improve the torque characteristics and the counter-rotating type is used to increase the relative rotational speed of the generator. Figure 1-16 shows the experimental set up and the measuring devices of the wind tunnel test. Model wind turbines of front stage were 3, 4, and 6 bladed propeller type and 0.6m in diameter. The rear stage ones were 2 and 3 bladed propeller type and lm in diameter. Test runs were conducted to determine

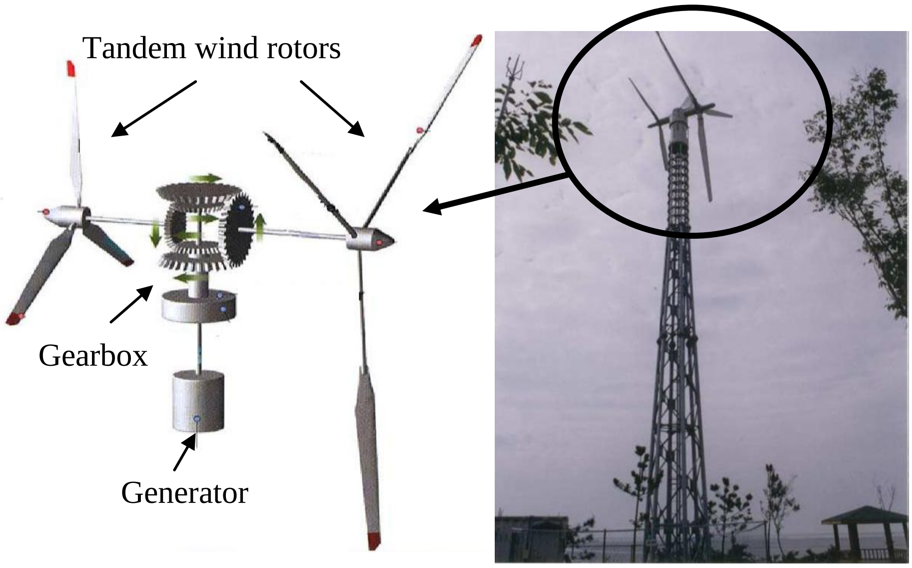


Fig. 1-15 Prototype of tandem wind rotors with gear box (54)

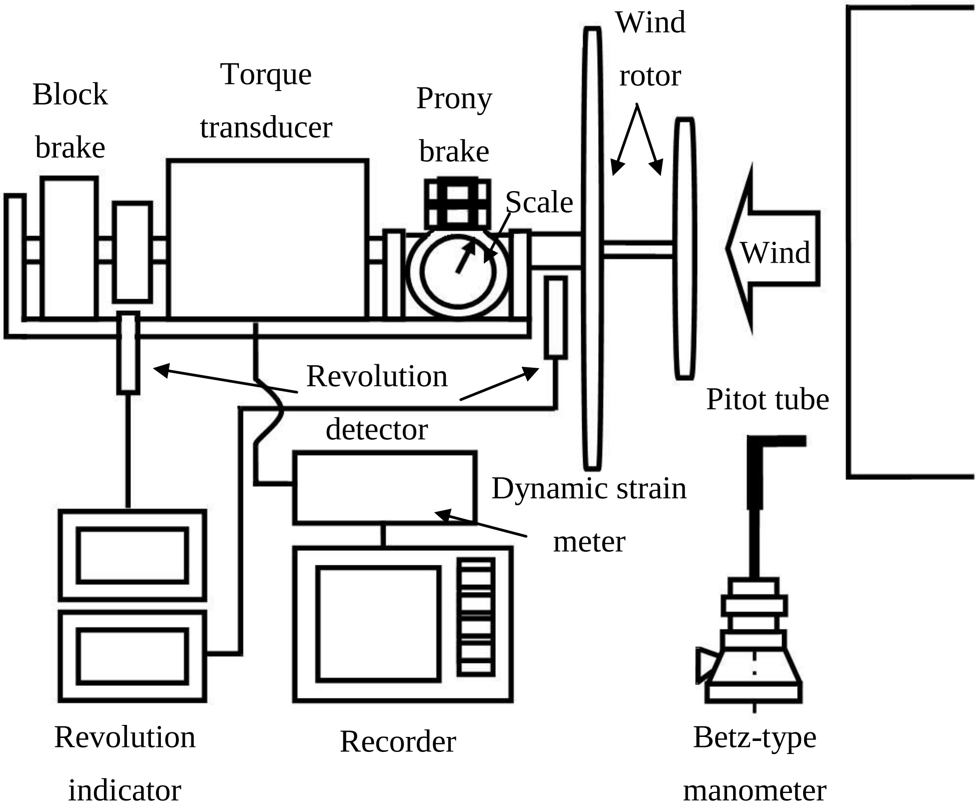


Fig. 1-16 Experimental apparatus of professor Ushiyama (55)

the torque characteristics of the rotor. The torque in was applied increasingly through a block brake, reading number of revolution and torque respectively. The torque coefficient C_M and the power coefficient C_P were calculated from these data. As for the counter-rotating type, same torque value was applied to both the front and the rear stage rotors while reading the number of revolutions and torque respectively.

The trial machine used to make the experiments consist of front stage of 6 bladed propeller type rotor diameter of 1.2m, and rear stage of 3 bladed propeller type rotor of diameter 0.8m. The power characteristics of the trial machine are shown in Fig. 1.17. From this figure it is shown that the higher the setting wind speed, the larger the output of the machine. The maximum output corresponding to each wind speed were 2.6W for 6m/s, 19.8W for 8m/s, and 38.9W for 10m/s respectively. The rated output of the tested generator was 36W at 950rpm, while the total rotational speed of the front and rear rotor of the tested machine was 768rpm at 10mls. Thus, the larger output than rated value could be obtained at lower rotational speed than rated rpm. These experiments showed that self-starting characteristics of co-axial type were improved by front wind turbines installed for two-bladed wind turbine. Also, relative rotational speed of counter-rotating type was increased, and test result of the trial machine demonstrated the technical possibility of counter-rotating type wind powered generator.

It is important to notice that all of these previous attempts use different concepts

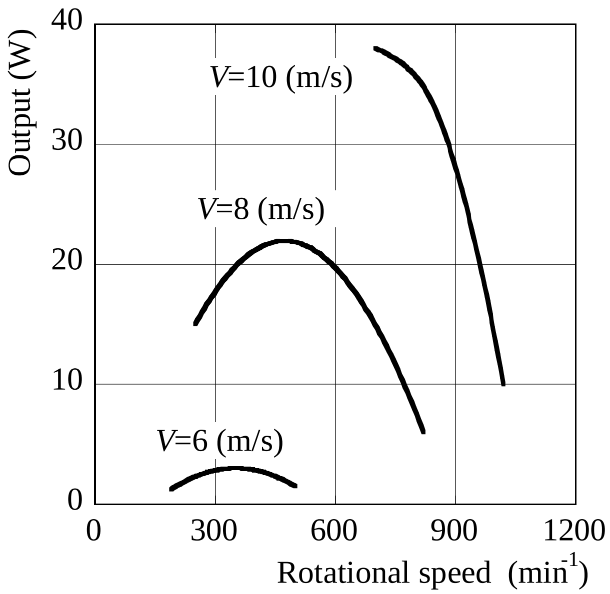


Fig. 1-17 Power characteristics [5]

than the concept used in this research because they used either gear boxes or pitch control mechanisms or even both. On the contrary, the operation of the proposed wind power unit using the tandem wind rotors in this work is in cooperation with the double rotational armature type generator without the need of the gearbox, and the pitch control mechanisms.

1.5 Objectives of this Study:

As was shown previously, the propeller type wind turbines are very effective to generate the electric power; however, these conventional turbines had some weak points that can be summarized as follows:

1. The size of the wind rotor must be correctly/appropriately selected in conformity with the wind circumstances. Although large-sized wind rotors generate high output at strong wind, they do not operate properly with weak winds. On the contrary, small-sized wind rotors are suitable for weak wind, but their power generation is low. This problem can be solved using the proposed wind power unit. The counter-rotation under the rated wind speed makes output higher in poor wind circumstances, while at a high wind velocity, it generates higher output than the single wind rotors.

2. It is necessary to be equipped with the brake and/or the pitch control mechanisms, to suppress the abnormal rotation and the generated overload at the stronger wind. This point is solved in the unique wind power unit because at higher wind velocities, the rear wind rotor rotates in the same direction of the front rotor (blowing mode) forcing the abnormal rotational speed of the front wind rotor to slow down without using brake and/or the pitch control mechanisms.

3. The fluctuation of the wind rotor speed may lead to a poor quality of the electrical power. In the proposed unit, the relative rotational speed between tandem wind rotors which corresponds to the electrical output frequency is adjusted automatically pretty well with response to the wind velocity keeping good quality of the electric power.

This work proposes/presents a new unique type horizontal wind power unit composed of the large-sized front wind rotor, the small-sized rear wind rotor and the peculiar generator with the inner and the outer rotational armatures as shown in Fig.

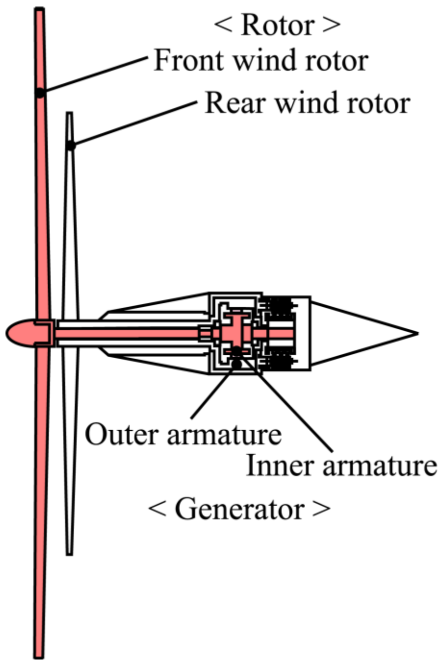


Fig. 1-18 Unique wind power unit

1-18. The front and the rear wind rotors drive the inner and the outer armatures. This unit is unique, as during the experiments on the small scale rotors, the rotational speeds of the tandem wind rotors are adjusted pretty well in cooperation with the two armatures of the generator in response to the wind speed. The rotational torque is counter-balanced between the inner and the outer armatures in the generator. As for the wind rotors, the rotational torque of the front wind rotor must equal that of the rear wind rotor, but in the opposite direction, while the rotational directions of both rotors/armatures are free. The rotational direction and speed of the rotor/armature are automatically determined in response to the wind circumstance. The output must be kept constant and this can be done if the rotors are designed so as to keep the relative rotational speed multiplied by the rotational torque equal a constant. The operation of the unique generator with double rotational armatures is verified in the field.

1.6 Thesis Contents:

This research is a part from series of studies that were done to develop and improve the performance of the intelligent wind power unit which was invented by Professor Toshiaki Kanemoto. This research has passed through many steps. First there was preparing of the main parts of the wind power unit which are used in the experiments, such as testing the unique generator of double rotational armatures, and was designing the tandem wind rotors that will be attached to the generator. Second there was a period for studying the performance of the previously mentioned generators equipped with the designed wind rotors in the field test. Lastly, many experiments were done to better understand the advanced technology of this unique wind turbine unit.

So, the chapters of this thesis were organized as follows:

- Chapter one is an introduction shows the importance of exploiting the renewable energy, concentrating on wind power. The topics tackled were the global warming, the fossil energy, the renewable energy, review on wind power units, previous work concerning single tandem rotors, and the objectives of this study. It was shown that the propeller type wind turbines are very effective to generate the electric power; however, these conventional turbines had weak points that is the size of the wind rotor must be correctly/appropriately selected in conformity with the wind circumstances. Although large-sized wind rotors generate high output at strong wind, but they do not operate properly at weak winds. On the contrary, small-sized wind rotors are suitable for weak winds, but their power generation is low. Also, it is necessary to be equipped with the brake and/or the pitch control mechanisms, to suppress the abnormal rotation and the generated overload at the stronger wind. Moreover, the fluctuation of wind rotor speed may lead to a poor quality of the electrical power. All these previous weak points can be solved through the superior operation of the proposed unique wind power unit.

- Chapter two concerns the proposal of a unique wind power unit. The topics discussed were the superior operations of the unique wind power unit, the development of the doubly fed induction generator with double rotational armature, the bench test and the experimental results. The development of the permanent magnet synchronous generator with double rotational armatures was also discussed, its bench tests, and experimental results. The design of the front and rear wind rotors was explained. Experiments were done to determine the optimal number of blades for both front and rear wind rotors, which were 3 blades for the front, and 5 for the rear wind rotor. Blades were designed through simple aerodynamic theories, namely blade element theory, using MEL012 profile, while the front wind rotor was 2m in diameter and the rear wind rotor was 1.33m.

- Chapter three concerns the experiments that were done on the unique wind power unit by the help of a pick-up type truck. The field site is described, data measuring tools shown, experimental procedures explained, and the performance of the unique wind power unit through using single and/or tandem wind rotors are analyzed. The effect of the setting of the rear blades, and the bulb loads on the operating conditions are discussed. Finally, trails of reasonable operations are introduced. The wind power unit could not operate properly at wind velocity less that 4 m/s. The performance of the wind power unit was affected markedly by the blade setting angles of both tandem wind rotors. The optimal values for single wind rotor was β_F = 0 at lower applied load, and 20 degrees at higher applied loads. In case of tandem wind rotors β_F =β_R =20 degrees gave relatively better response to the wind velocity.

- Chapter four is a discussion for the advanced technologies that were done as a step for optimizing the performance of the unique wind power unit. Different factors were examined to notice their effect on the performance, such as the aerofoil cross sectional profile of the rotor blades, including the chord and the camber. Distance between both tandem wind rotors was tested to find the reasonable axial distance between them. When using cambered blades instead of flat blades, the maximum output coefficient of the cambered blade increased 1.6 times more than that for the flat blade, while the relative tip speed ratio was increased also by nearly 1.4 times. The optimal diameter ratio between the rear and the front wind rotors that leads to relatively high output was found at D=0.84.

- Chapter Five shows the conclusions from this study. This is followed by the acknowledgments and the references.

Chapter 2

Preparation of Wind Power Unit

The author has contributed in developing the unique wind power unit that has superior operations, and smart behavior with response to the wind circumstances. This chapter discusses the superior operation of the unique wind power unit, the bench tests on the peculiar generators developed by the author, and the design of both tandem wind rotors.

2.1 Superior Operation of Unique Wind Power Unit

As in the case of upwind type as shown in Fig. 2-1, when the large sized front

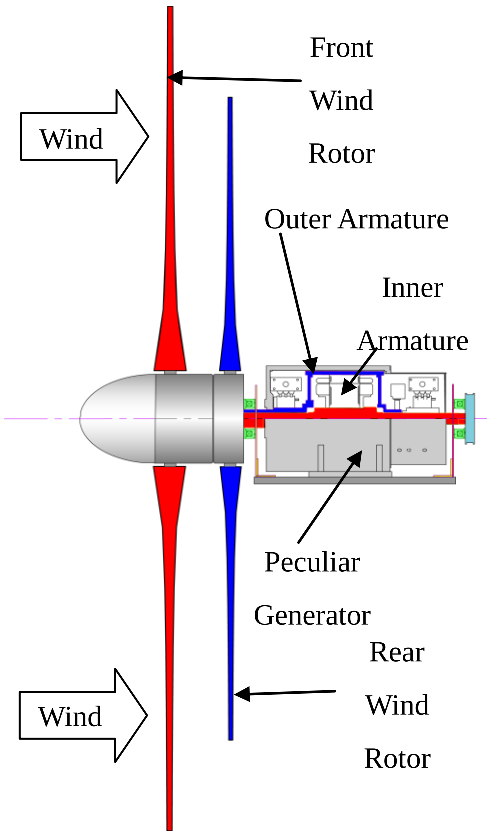


Fig. 2-1 Upwind type wind power unit

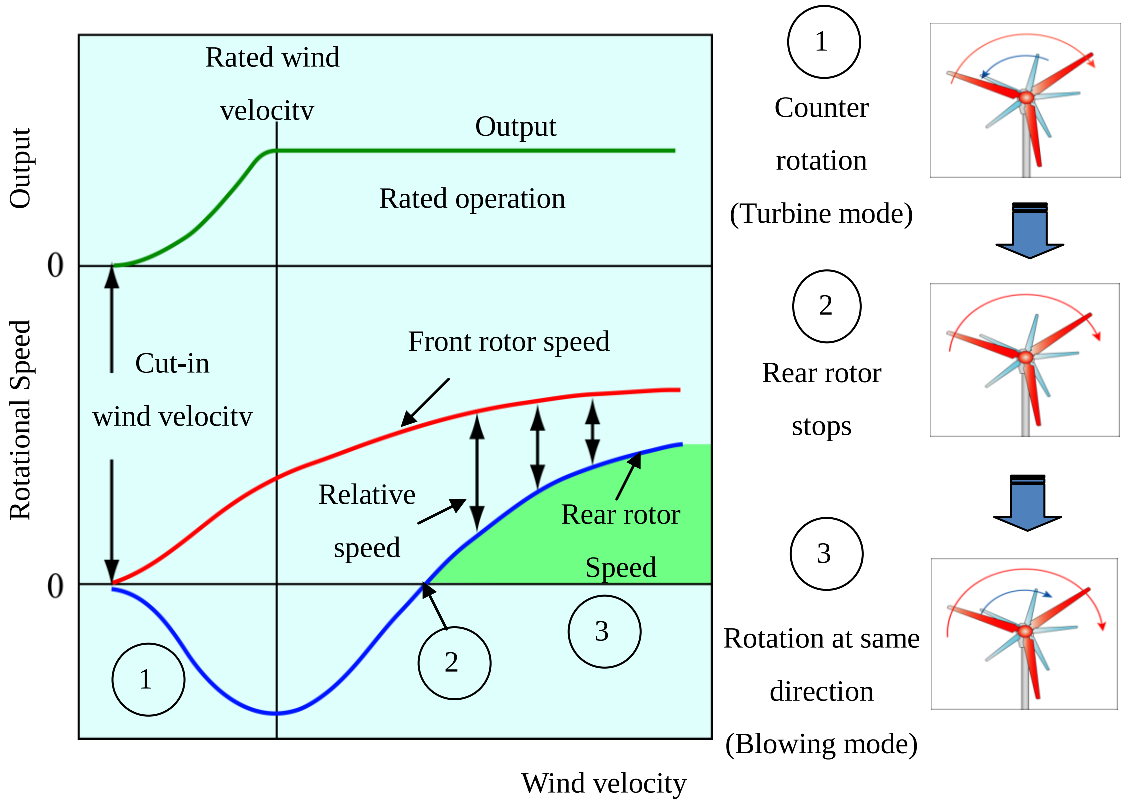


Fig. 2-2 Superior operations of unique wind power unit

wind rotor rotates, torque develops in the inner rotational armature of the peculiar generator. This torque is counter-balanced by the torque generated at the outer armature in cooperation with the torque generated from the rear wind rotor. So, as for the wind rotors, the rotational torque of the front wind rotor must be the same, in the opposite direction, as that of the rear wind rotor, but the rotational directions of both the rotors/armatures are free. The rotational direction and speed of the rotor/armature are automatically adjusted in response to the wind circumstance, as shown in Fig. 2-2.

Through this figure, it can be seen that both wind rotors start to rotate at a low wind speed, namely the cut-in wind speed, but the rear wind rotor counter-rotates against the front wind rotor. The increase of the wind speed makes rotational speeds of both wind rotors increase, while the rotational speed of the rear wind rotor appears to be faster than that of the front wind rotor because of its smaller size. The rear wind rotor reaches the maximum rotational speed at the rated wind speed. Below the rated wind velocity, both rotors rotate at the best efficiency points. Over the rated wind velocity, the rated operation starts, where the output is kept constant. With more increment of the wind velocity over the rated value, the rear wind rotor decelerates gradually, stops then begins to rotate at the same direction of the front wind rotor so as to its torque coincides with the larger rotational torque of the front wind rotor.

Such behavior of the rear wind rotor happens because the smaller sized rear wind rotor can not generate an equal counter torque value against the attacking wind during rotating at the turbine mode (counter direction to front rotor). When the rear wind rotor rotates in the same direction to front rotor, the blowing mode forces the abnormal rotational speed of the front wind rotor to slow down. As a result, the above operating conditions enables it successfully to guarantee good quality of the electric power, namely power supply frequency, and output in the rated operation without the conventional brake and/or the pitch control mechanisms. That is, the relative rotational speed between the front and the rear wind rotors affects directly the quality of the electric power. The power supply frequency can be kept constant when the wind rotors are designed so as to keep their relative rotational speed constant. The output can also be kept constant when the wind rotors are designed so as to keep the value, which is the relative rotational speed multiplied by the rotational torque, constant. Moreover, the counter-rotation under the rated wind speed makes the output higher in the poor wind circumstances, which is a remarkable advantage for the area which has no acceptable wind circumstance at the power generation such as found in Japan.

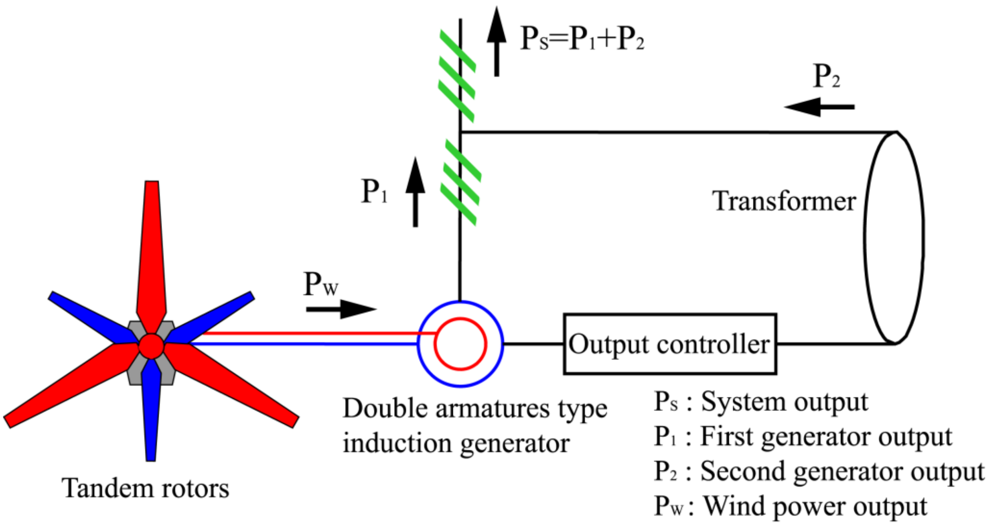


Fig. 2-3 System diagram of double armature type induction generator

In order to test the performance of the unique wind power unit in the field, preparations of the peculiar generator was done, and tandem wind rotors were designed as follows.

2.2 Double Rotational Armature Type Doubly Fed Induction Generator

The author has contributed in developing the double rotational armature type doubly fed induction generator without the conventional stator, to drive successfully the tandem wind rotors. This generator is installed in the large-scale unit for the grid-connected electric power system. Figure 2-3 shows the system diagram which has the advantage that it is not necessary to control mechanically the rotational speed because the revolving electromagnetic field is induced from the grid-connected electricity. The rotational speed and the output can be easily adjusted by the frequency modulation, namely the rotational slip control of the inner armature, through the inverter. Besides, the initial and running costs are less than those of the synchronous generator.

2.2.1 Specifications of the generator

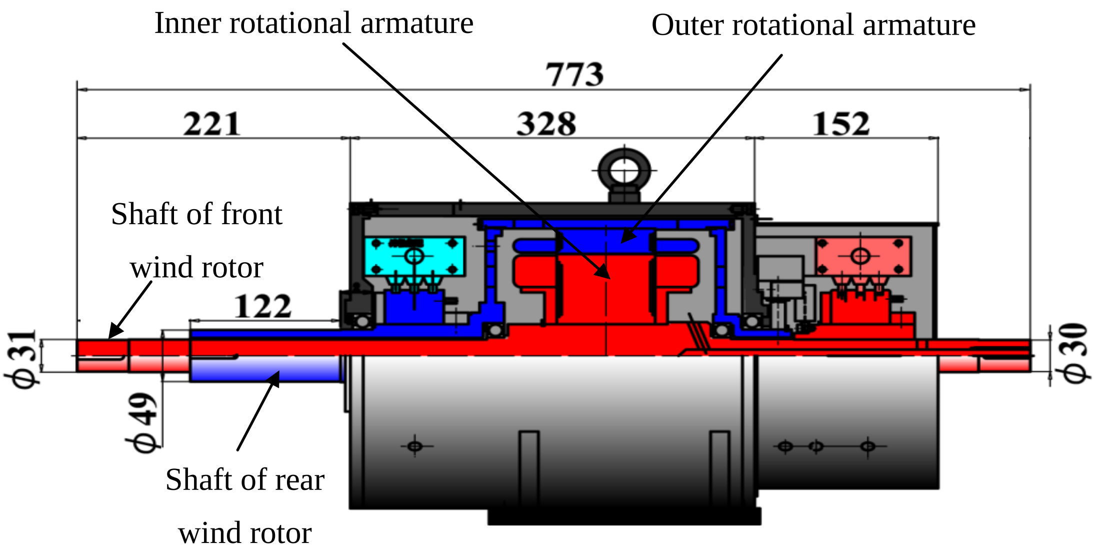


Fig. 2-4 Doubly-fed induction generator with double rotational armatures

Figure. 2-4 shows the dimensions of the doubly fed induction generator. There are two feed circuits for this generator type; namely primary and secondary feed circuits. The primary feed circuit represents the output of the generator, and connected to the outer rotational armature. The secondary feed circuit represents the input and is connected to the inner rotational armature. The synchronous speed of this generator is N_T=900 min^{-1} where $N_T = N_F - N_R$ (N_F and N_R are the outer and the inner rotational speeds, and give the positive value in the N_F direction). The rated output power is 1.2KW, while the output voltage is 200V, the current is 3.5A, the frequency is 60Hz, the number of poles p is 8, and the rotational speed ranges from 360 to 1260 min^{-1}.

As from the basic concepts of the induction generator, the rotors always rotates at a relative speed slightly different than the synchronous speed (45) (57). The difference between the synchronous speed N_S and the rotors relative speed N_T is termed as the slip of the generator. Thus,

the slip S is given by: $$S = (N_S - N_T)/ N_S \quad (2.1)$$

While the synchronous speed of the induction generator is given by:

$$N_S = 120f/p \quad (2.2)$$

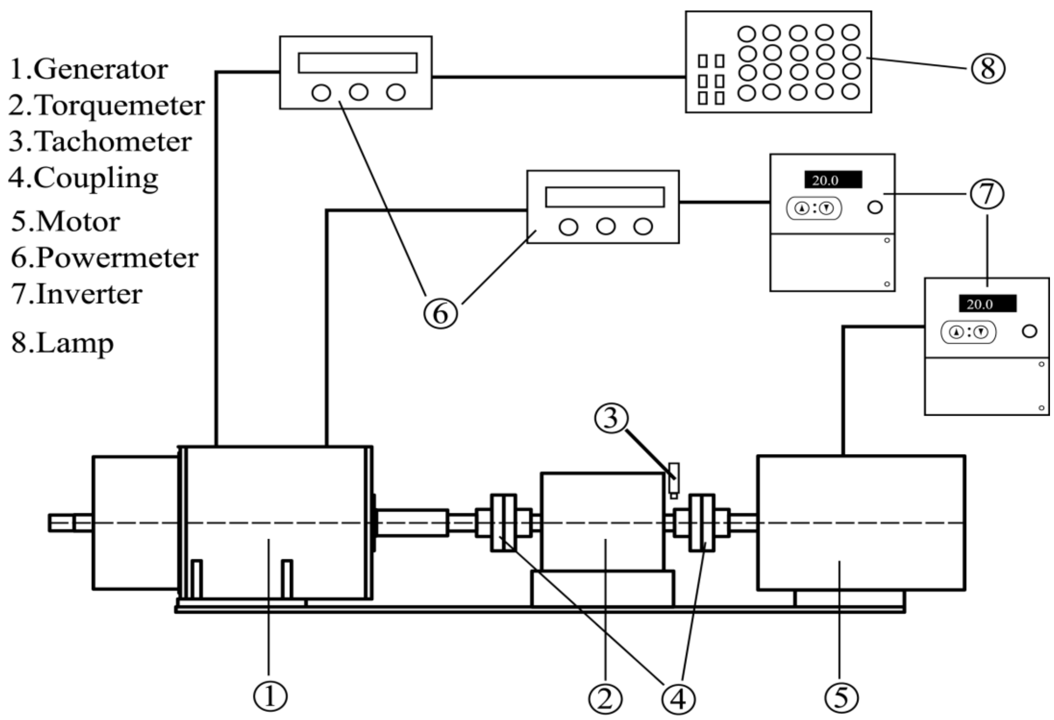


Fig. 2-5 Apparatus of experiments.

2.2.2 Experimental apparatus

Figure 2-5 shows the apparatus used for the experiments. The work of the tandem wind rotors was replaced by a motor. The motor shaft was connected to the shaft of the inner armature while the shaft of the outer armature of the generator was kept stationary because the electrical characteristics depend only on the relative rotational speed between both armatures. The rotational speed of the motor which represents the relative speed of the front and the rear wind rotors was controlled by using and inverter. Another inverter was used to control the input frequency of the secondary circuit of the generator. Torque was measured using a torque meter. The output power was consumed through set of lamp loads which were controlled manually through on/off switches.

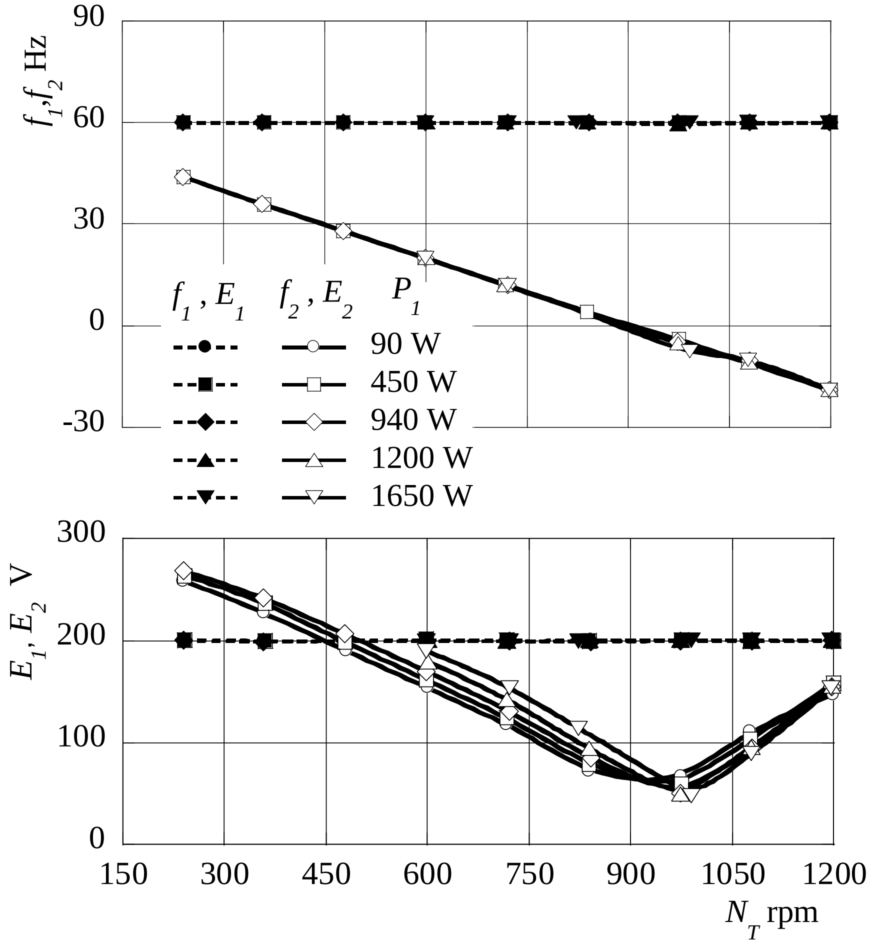


Fig. 2-6 Effect of external Load, and relative tip speed on frequencies, and voltages

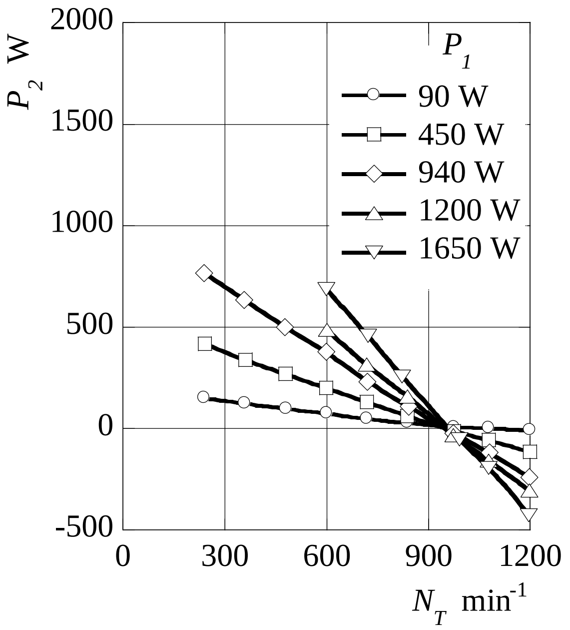


Fig (2-7) Effect of external load on the electrical output

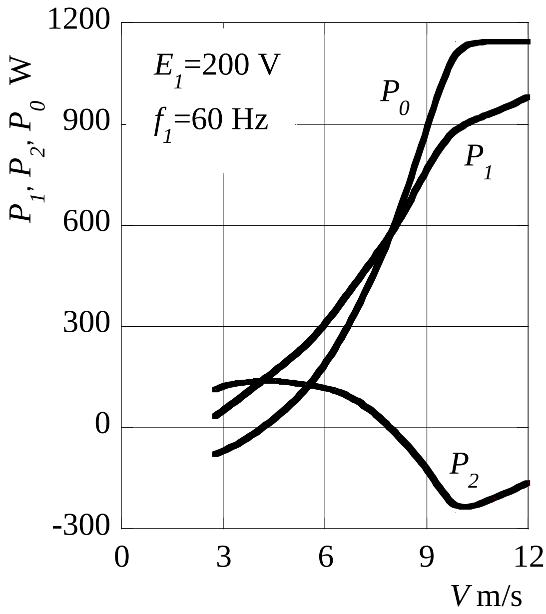


Fig. 2-8 Power against wind speed

2.2.3 Bench tests

Bench tests were done while keeping the output frequency f_1 constant and equals 60Hz, and also keeping the output voltage E_1 constant and equals to 200V through using different load values. This situation represents the actual work needed from the generator when it is connected to the grid. Figure 2-6 shows the characteristics where *P*, *f* and *E* are the output/input, the frequency and the voltage, while subscripts 1 and 2 represent the values of the outer and the inner armatures.

As $N_T = N_F - N_R$, and $N_S = 120f/p$ then $N_T = 120/p(f1-f2)$ (2.3)

The input frequency f_2 is in inverse proportion to the relative rotational speed N_T irrespective of the output P_1, though the phase must be changed at the higher relative speed than the synchronous speed N_T=900 min^{-1}. The input voltage E_2 does not depend only on N_T but also on P_1, namely the load. The input P_2 comes to be negative at the higher rotational speed than the synchronous speed N_T=900 min^{-1}, as shown in Fig. 2-7. That is, P_2 changes fruitfully from the input to the output, and the net output from the generator is $P_0 = P_1 - P_2$. So, in order that the generator works fruitfully, it must be rotated by a relative speed N_T higher than the synchronous speed of the generator

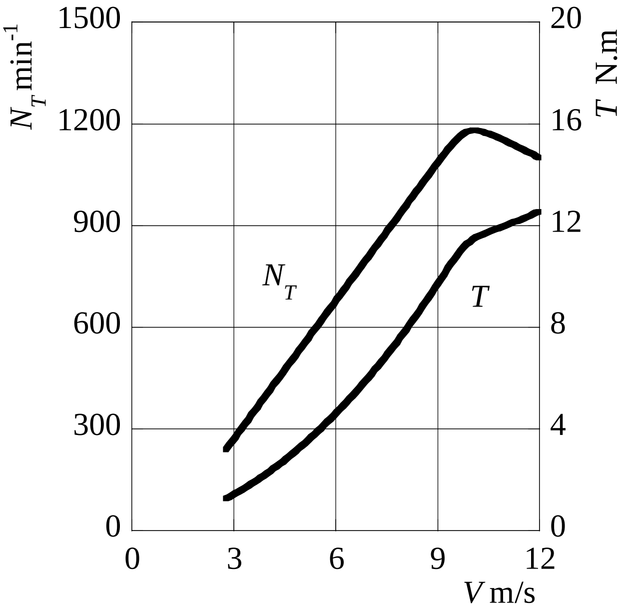


Fig. 2-9 The relative tip speed and the torque against the wind speed.

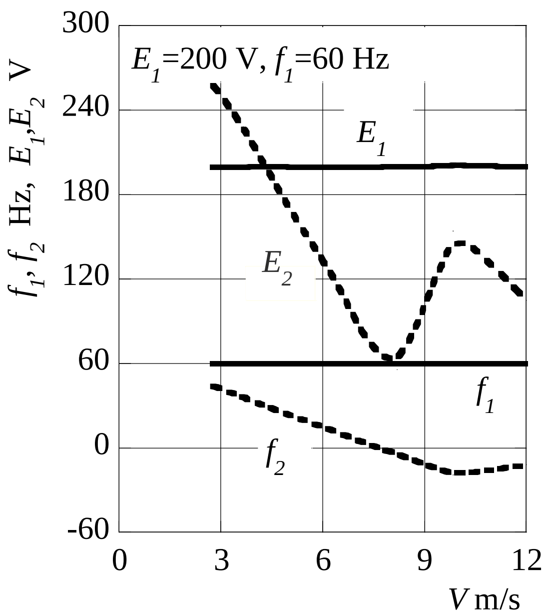


Fig. 2-10 Frequencies and voltages against the wind speed

(generating mode), because below this speed it will need to consume P_2 from the source (motoring mode)

The characteristics of the generator are also presented against the wind speed. Figure 2-8 shows the output P_1, the input P_2, and the net output power P_0, while Fig. 2-9 shows the relative rotational speed N_T and the rotational torque T. Figure 2-10 shows the output and input voltages E_1, E_2 and the output and input frequencies f_1, f_2. So, if tandem wind rotors could be design so that it fulfills the values of the relative rotational speed N_T and the rotational torque T, and if the input frequency f_2, and the input voltage E_2 could be adjust to get the output frequency f_1, and the output voltage E_1, then a constant and steady net output power P_0 could be obtained at the rated operation of the generator.

2.3 Double Rotational Armature Type Synchronous Generator

The author has also contributed in developing the permanent magnet synchronous generator without the conventional stator, to drive successfully the tandem wind rotors in the field tests. This synchronous generator was used successfully in hydroelectric turbines. The main difference between this type and the previously mentioned induction generator, is that there is no existence for the slip.

2.3.1 Specifications of the generator

The dimensions of the synchronous generator is shown in Fig. 2-11. It is an AC

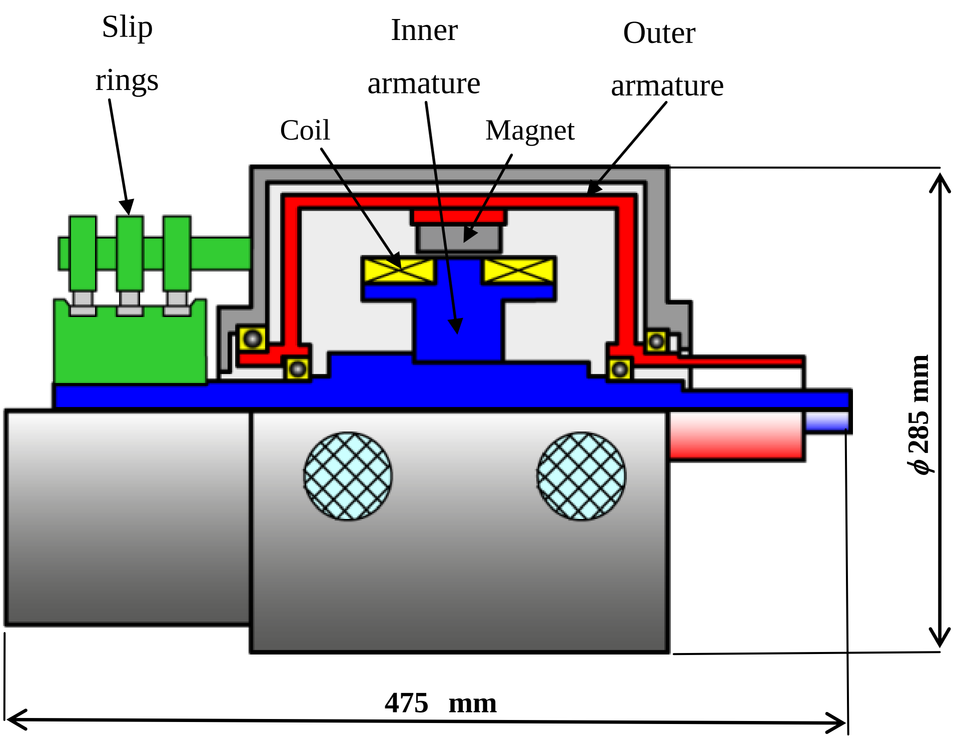


Fig. 2-11 Double rotational armature type synchronous generator

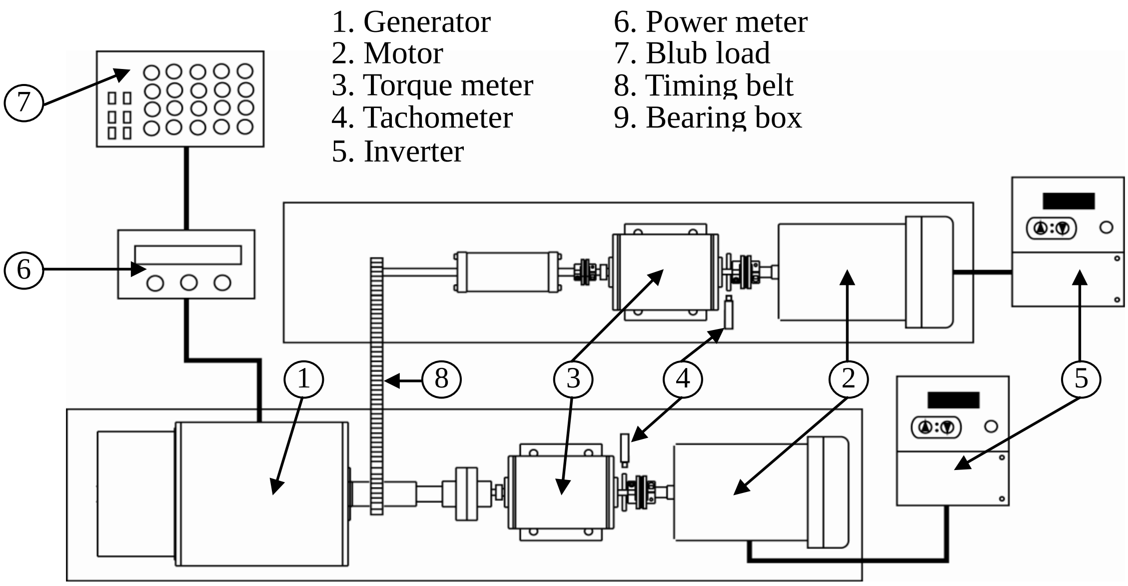


Fig. 2-12 Synchronous generator bench test apparatus

3-phase, with p=4 poles, output P=1 kW, the induced frequency f=50 Hz, and the induced voltage E=100 V while the relative rotational synchronous speed between the double armatures is N_T=1500 min^{-1} at the rated operation. This value can be easily calculated from equation (2.2) that also can be applied on this generator type as follows:

$$f_1=50 \text{ Hz}, \quad p=4 \text{ poles, then} \quad N_T=120 \text{ x } 50 / 4 = 1500 \text{ min}^{-1}$$

2.3.2 Experimental apparatus

Figure 2-12 shows the apparatus used for making the experiments. These experiments were done to know/grasp the characteristics of the permanent magnet synchronous generator. The armatures were driven by two isolated motors instead of the tandem wind rotors. The motor was directly attached to the shaft of the inner armature, while another separate motor is attached to the shaft of the outer armature through a timing belt. The output of the generator was consumed through lamp loads through a wattmeter. Torques on the shafts of the motors were measured through torque meters.

2.3.3 Bench tests

Bench tests were made in order to know the fundamental characteristics of the

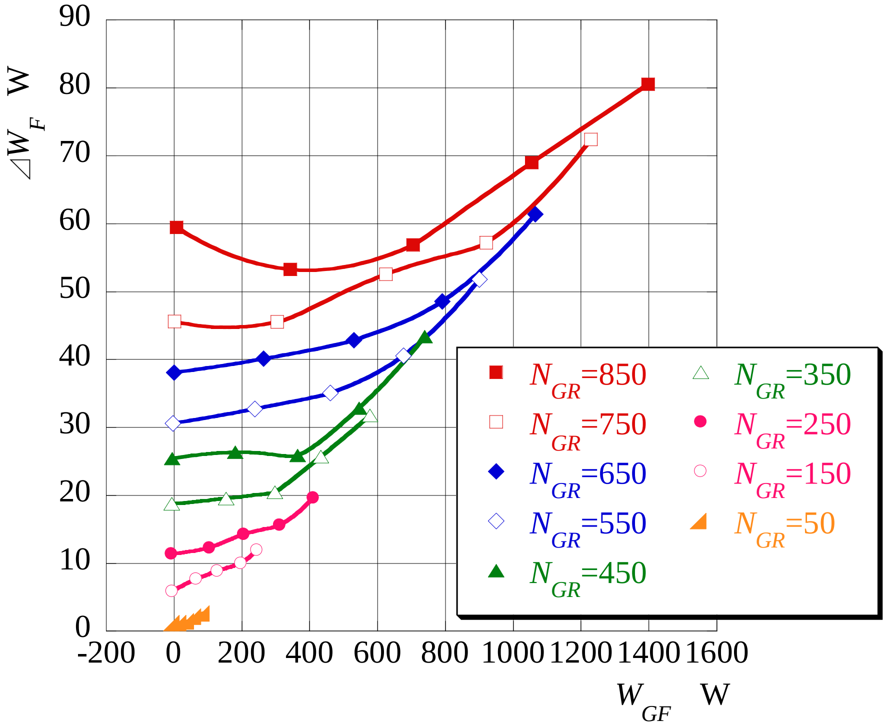


Fig. 2-13 Values of the timing belt and bearing losses

generator, before supplying to the field tests. In general, the inner and the outer armatures rotate at counter directions at the beginning of the motion, so that to counter balance the torques of both armatures (T_{GR}=T_{GF}). Losses from the timing belt and the bearings can be measured through equaling the speeds of both the inner and outer armatures N_{GR}, and $N_{GF.}$ Figure 2-13 shows the values of frictional losses of the timing belt and bearings. Figure 2-14 shows the rotational torques T_{GF} and T_{GR} for various relative speeds N_T against the induced electric current I, where these torques include the mechanical torques in the generator and T_{GR} is given by the absolute value. That is, these are the shaft torques in practical use of the field tests. The rotational torques of both shafts T_{GF}, T_{GR} are directly proportional to the induced electric current I irrespective of the rotational speeds and the output but T_{GF} is slightly larger than T_{GR} due to the mechanical torque of the larger bearings.

Continuously, experiments were done through applying different values of loads which took step increasing values from 0 (no load) till 1000W. When no load was applied, it was found that the induced voltage was linearly proportional with the rotational speeds of both the inner and outer armatures of the generator N_{GR}, and N_{GF} as

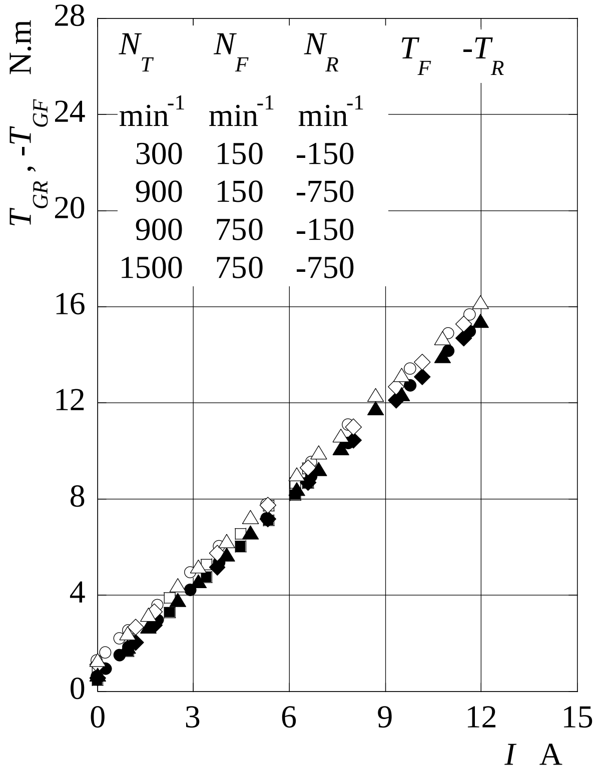


Fig. 2-14 Shaft torques against the induced electric current

shown in Figures.

Experiments were done so that the outer armature rotational speed N_{GF}, and the inner armature rotational speed N_{GR} took different step values, where the output P_G (=Torque x $2\pi N_T/60$), the induced voltage E, and the electrical efficiency η_G of the generator against induce current I. The output increases with the increase of the induced voltage E at the same I, while E is proportional to the relative rotational speed N_T and I determine the rotational torque [(57)]. Figure 2-15 shows the relationship between the outer armature rotational torque T_{GF} and the inner armature rotational torque T_{GR}, in keeping the rotational speed of the outer armature constant at N_{FG}=750 min^{-1}, while changing the rotational speed of the inner armature N_{RG} and the output. Rotational torques do not include the mechanical torques such as bearings in the generator, and T_{GR} is given by the absolute value though the direction of T_{GR} is against T_{GF}. It is obvious that both torques show the same absolute value irrespective of the relative rotational speed and the output, because the rotational torque should be always dynamically counter-balanced between the inner and the outer armatures. It is important to notice that the manufacturing of this unique generator, and also the experiments were done by

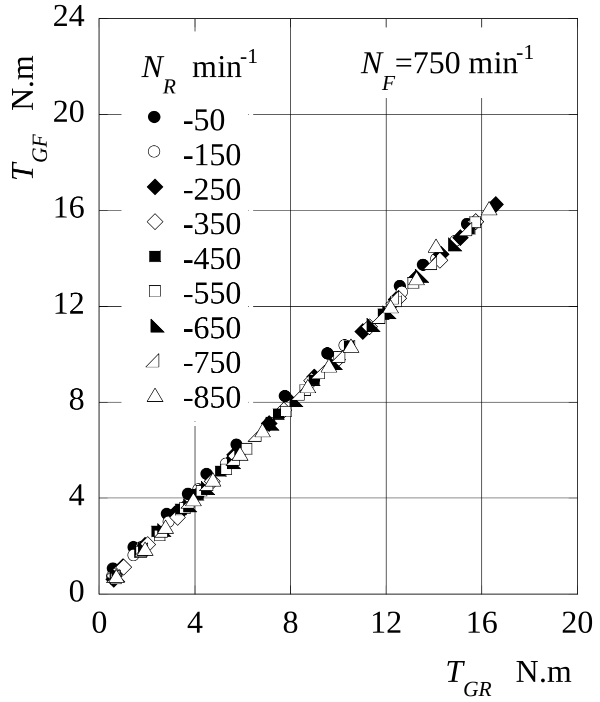


Fig. 2-15 Relationship between the torques of the inner and the outer armatures

the cooperation with highly professional experts and personnel specialized mainly in the field of electric generators.

The next step will be designing the tandem wind rotors that will be used in experiments.

2.4 Design of Tandem Wind Rotors

At the beginning, and before presenting the steps of designing the wind rotor blades, it is important to tackle some basic topics concerning the energy available in wind which is basically the kinetic energy of large masses of air moving over the earth's surface. Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms. The efficiency of converting wind to other useful energy forms greatly depends on the efficiency with which the rotor interacts with the wind stream. In order to design the wind turbine rotor, some important topics should be recalled. First, the fundamental principles involved in the wind energy conversion process should be discussed.

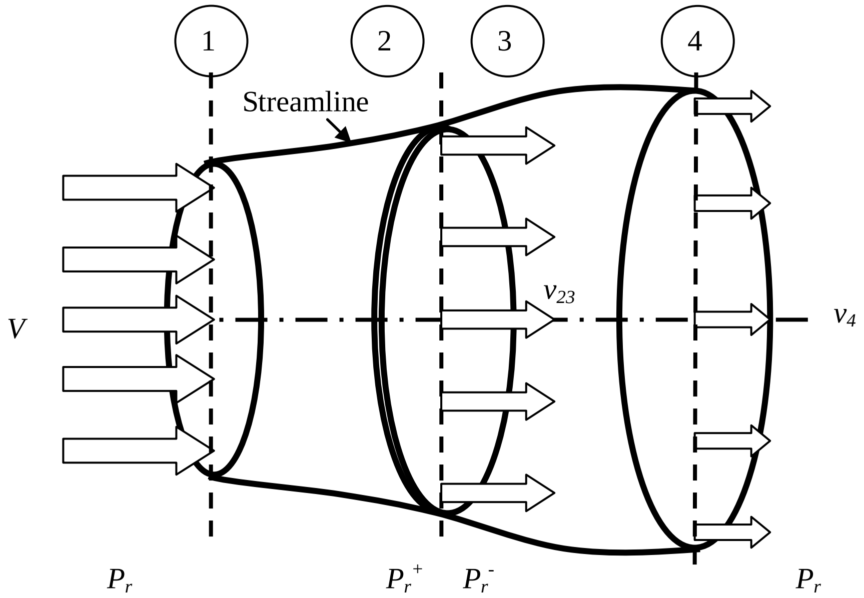


Fig. 2-16 Wind power extracted though rotor blades

2.4.1 Power extracted from the wind

Assume an area through which air is blowing, such as shown in Fig. 2-16 [58] [59]. Disk shown represents the area swept by the rotor blades. Applying Bernoulli principles between positions (1), and (2), then between (4), and (3) we have:

V, and *P* are upstream wind velocity, and pressure at the entrance of the rotor blades, at position (1)

v_{23}= velocity passing the area swept by the rotor blades, at both positions (2), and (3).

P_r^+, and P_r^- are the pressures at positions (2), and (3).

v_4, and P_r are downstream wind velocity, and pressure at the exit of the rotor blades, at position (4).

$$0.5\rho V^2 + P_r = 0.5\rho {v_{23}}^2 + P_r^+ \tag{2.4}$$

$$0.5\rho {v_4}^2 + P_r^- = 0.5\rho {v_{23}}^2 + P_r \tag{2.5}$$

$$P_r^+ - P_r^- = 0.5\rho (V^2 - {v_4}^2) \tag{2.6}$$

Thrust will be as

$$T = A(P_r^+ - P_r^-) = 0.5\rho A(V^2 - v_4^2) \qquad (2.7)$$

Thrust is also be given as the change of momentum, where Q is the volume flow rate, so;

$$T = \rho Q(V - v_4) = \rho A v_{23}(V - v_4) \qquad (2.8)$$

Equalizing equations (2.10), and (2.11)

$$0.5\rho A(V^2 - v_4^2) = \rho A v_{23}(V - v_4) \qquad (2.9)$$

$$v_{23} = 0.5(V + v_4) \qquad (2.10)$$

There is a value of a that maximize the power extracted from wind. Previous velocities then can be expressed in terms of a as follows:

$$v_{23} = V(1 - a) \qquad (2.11)$$

Then from equations (2.7), and (2.8)

$$v_4 = V(1 - 2a) \qquad (2.12)$$

The actual power extracted by the rotor blades is the difference between the upstream and the downstream wind powers. That is

$$P_a = 0.5\rho A v_{23}(V^2 - v_4^2) \qquad (2.13)$$

$$P_a = 0.5\rho AV(1-a)\left[V^2 - V^2(1-2a)^2\right]$$
$$P_a = 0.5\rho AV^3(1-a)\left[1-(1-2a)^2\right]$$
$$P_a = P(1-a)\left[1-(1-2a)^2\right] \qquad (2.14)$$

To get the value of a that gives the maximum extracted power, equation (2.17) is differentiated with respect to a then equalized with zero $(dP_a / da = 0)$, which will lead to a=1, or a=1/3. Value of a=1 is rejected, because at which power extracted will equal zero, while at a=1/3 power has a maximum value of $P_a = 16/27P$. This means that to get maximum power extracted from the wind, the velocity of wind passing through the area swept by the rotor blades should equal 2/3 of the upstream velocity, while the velocity at the downstream will equal to 1/3 of the upstream one. So, in general,

$$P_a = 0.5\rho A V^3 C_P = C_P P \qquad (2.15)$$

Or

$$C_P = P_a / P = P_a / (\rho A V^3 / 2) \qquad (2.16)$$

Where C_p here represents the fraction of the upstream wind power, which is captured by the rotor blades. The remaining power is discharged or wasted in the downstream wind. In case of tandem wind rotors, a part of this remaining power rotates the rear wind rotor which is located just behind the front wind rotor. The factor C_p is called the power coefficient of the rotor or the rotor efficiency which has a maximum value called "Betz limit" which equals $C_p = 16/27 = 0.59$ as was shown previously. In practical designs, the maximum achievable C_p is below 0.5 for high-speed, two-blade turbines, and between 0.2 and 0.4 for slow speed turbines with more blades as shown in Fig. 2-17.

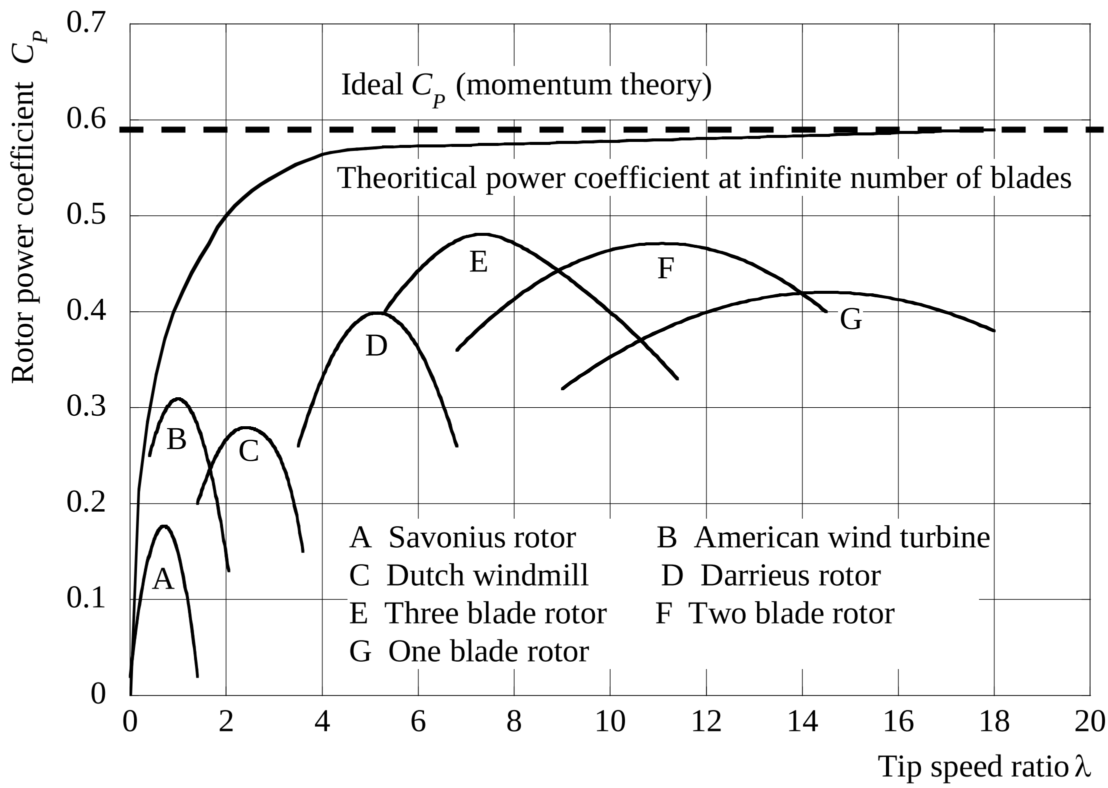


Fig. 2-17 Power coefficients of wind rotors of different designs (26)

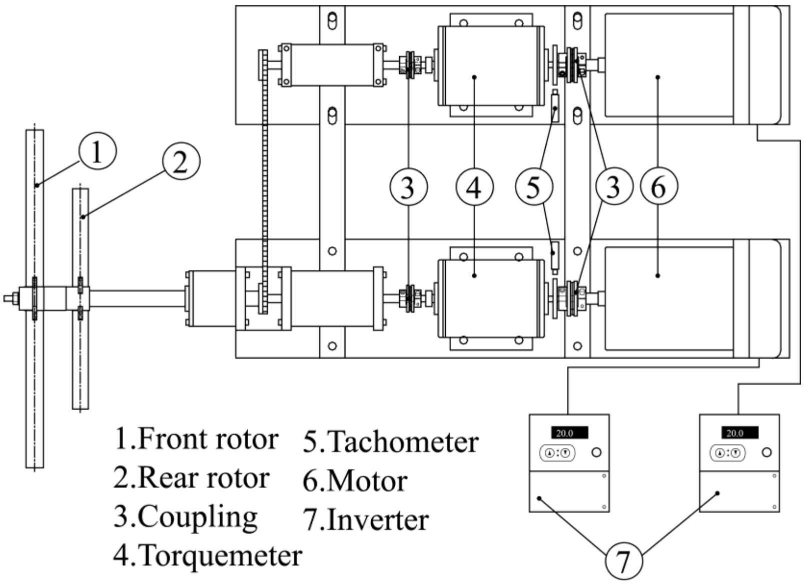


Fig. 2-18 Predictable operation of the proposed unit

2.5 Determination of Optimal Blade Numbers

It is important to determine how many blades should be used for both front and rear wind rotors. For modern wind power units, 3 blades are commonly used more than 2 blades because of its advantages not only because it generates more output, but also it is dynamically more stable. The author prepared the apparatus that was used to determine the optimal blade numbers of tandem wind rotors.

2.5.1 The apparatus used for experiments

The model shown in Fig. 2-18 is composed of the tandem wind rotors and the conventional induction generator whose stator is directly connected to the rear wind rotor shaft and plays the role of the outer rotational armature, was preliminarily prepared and set at the outlet of the wind tunnel (the nozzle diameter is 600mm). As was mentioned before, the rotational direction of the rear wind rotor changes in response to the wind speed as predicted above, while the front wind rotor rotates in the same direction.

2.5.2 Simulating the work of the peculiar generator

It is not easy, however, not only to know the rotational torque but also to get the fruitful materials for optimizing the blade profile, using the above model. Continuously, the shafts of the wind rotors were connected directly and respectively to two isolated motors which were controlled using inverters in place of the peculiar generator, as shown in Fig. 2-18. In this apparatus, the rotational torque of the rear wind rotor must be forced to coincide with the rotational torque of the front wind rotor, replacing the

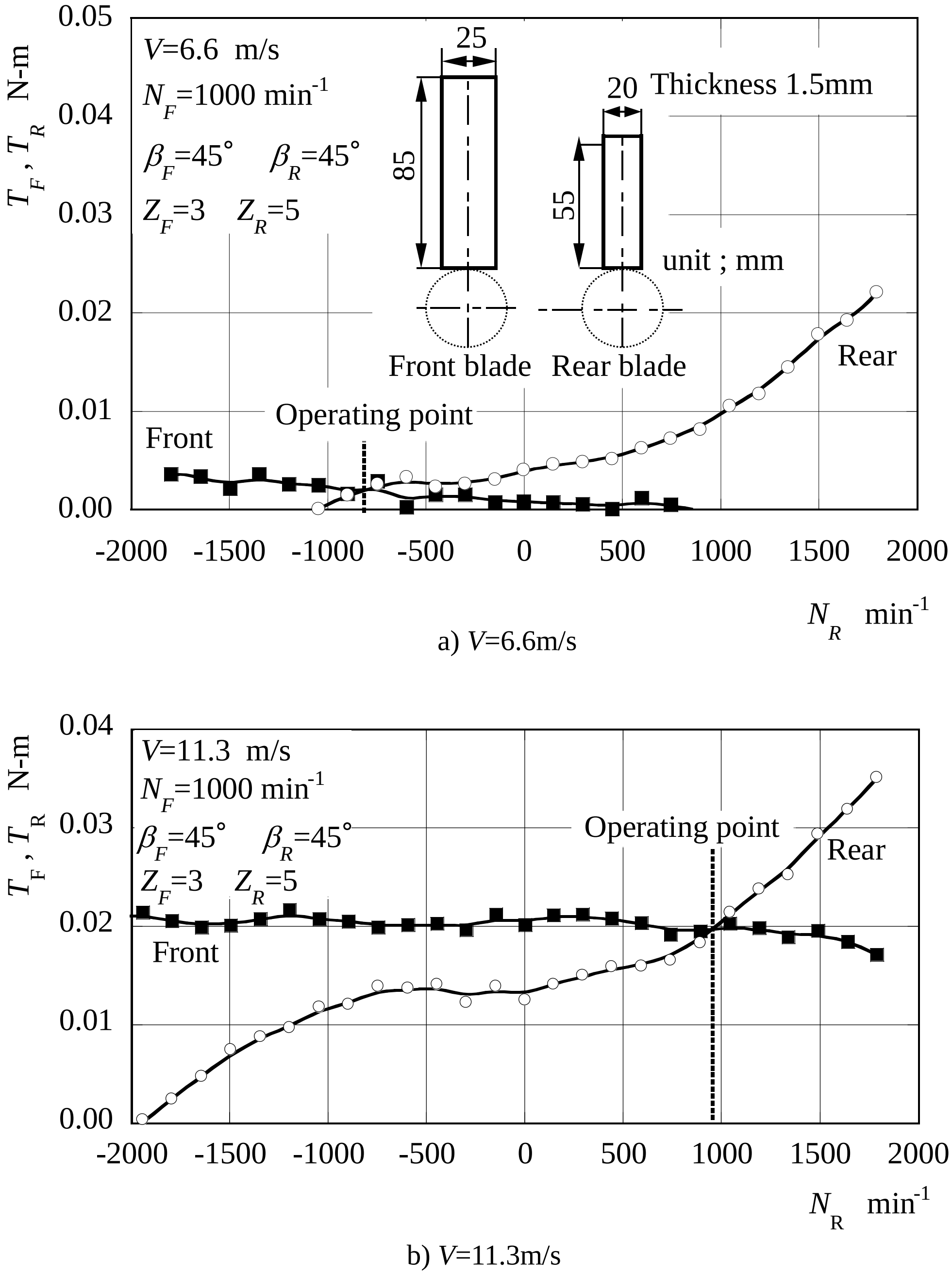


Fig. 2-19 Torque characteristics and operating point

armature works. Figure 2-19 shows the rotational torque T (subscripts F and R mean the front and the rear wind rotors) against the rotational speed of the rear wind rotor N_R, in keeping the rotational speed of the front wind rotor N_F and the wind speed V constant (N_F=1000min^{-1}, V=6.6m/s and 11.3m/s). The rotational torque T is evaluated here without the mechanical torque of the bearings and the pulley system, which are pre-examined using this apparatus without the wind rotors. The torque T_R is naturally a negative value but was presented with the positive value in this figure, to be compared easily with T_F. The negative rotational speed of the rear wind rotor N_R is in the turbine mode, and the positive speed is in the blowing mode. The torque of the front wind rotor T_F is scarcely affected by the rotational speed N_R, though T_F is affected by the wind speed V. On the contrary, the torque of the rear wind rotor T_R is affected obviously by not only the wind speed but also the rotational speed of the rear wind rotor. The torque T_R becomes large with the increase of the wind speed V and the rotational speed N_R. The tandem rotors run at the operating point where T_F=-T_R, as mentioned above and marked in Fig. 2-19.

2.5.3 Blades used in experiments

The flat blades, which were labeled the flat blade A, with the thickness of 1.5mm were prepared as shown in Fig. 2-20, to verify fundamentally the superior operation of the tandem wind rotors. The diameter of the front wind rotor equipped with the blade AF is d_F =550mm and the rear wind rotor equipped with the blade AR is d_R=390mm, where the diameter of both cylindrical hub is 50 mm, and front hub does not have the nose cone. The rotational torque of the wind rotor was counter-balanced by the rotational speed controller, namely the inverter, in accordance with the above procedure. The maximum Reynolds number based on the blade chord and relative velocity at the blade tip is R_{emax}=5x10^4 in the experiments. Unfortunately, it is impossible to make the Reynolds number as large as the prototype, on account of the wind tunnel capacities. The model tests do not give the absolute values of the prototype, but it does indicate the best materials for discussions on the wind rotor work as the first step.

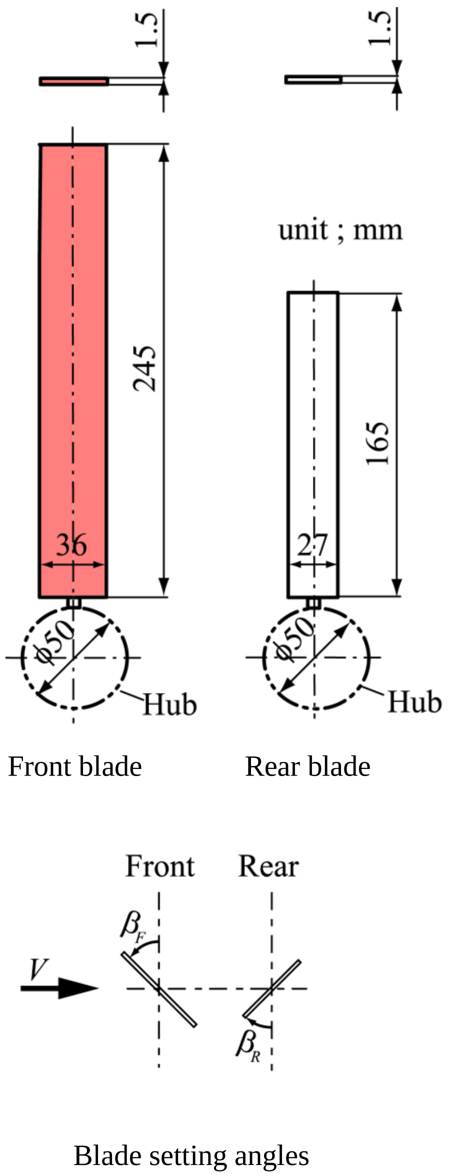
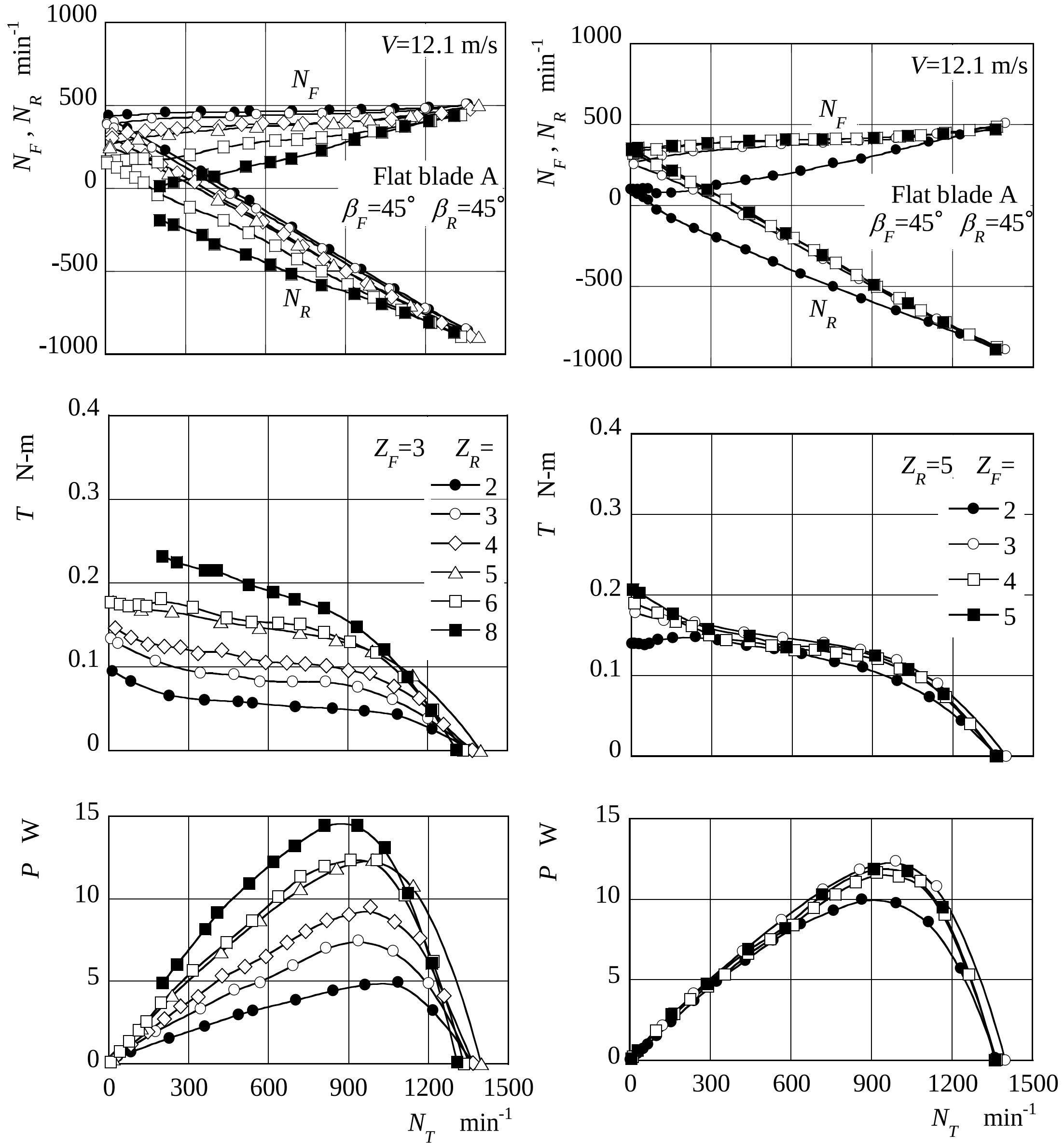


Fig. 2-20 Flat blade A

2.5.4 Optimizing the blade number

Using the previously described apparatus, experiments were done to study the effects of the blade number on the characteristics of the wind rotors as shown in Fig. 2-21, where the front and the rear blade setting angles are $\beta_F = \beta_R = 45$ degrees. It is important to pay attention to the behavior of the rear wind rotor. That is, the rear wind rotor must run not only in the opposite direction (counter-rotation) against the front wind rotor



a) Effect of front blade number

b) Effect of rear blade number

Fig. 2-21 Fundamental characteristics of tandem rotors

when the relative rotational speed N_T is faster or the rotational torque is smaller, but also in the same direction when the relative rotational speed is slower or the rotational torque is larger. As shown in Fig. 2-21(a), the rotational torque T and the output P are scarcely affected by the number of the front blades Z_F, but the front wind rotor with two blades (Z_F=2) is not acceptable because of the absence of the counter-rotation. This figure suggests that the optimal blade number of the front wind rotor is Z_F=3 judging from the rotational direction and the output.

On the contrary, the rear blade number Z_R has great influence on the characteristics as shown in Fig. 2-21(b). The rotational speed of the front wind rotor N_F becomes obviously slower and the speed of the rear rotor N_R becomes faster, as the absolute value, with the increase of the blade number of the rear wind rotor. Furthermore, the rear wind rotor with many blades is not acceptable as for the counter-rotating case but makes the rotational torque and the output increase. Taking account of the counter-rotating situation and the output, the optimal blade number of the rear wind rotor is Z_R=4-6. These results, however, may not be applied to the prototype as they are because these are special case obtained from the flat blades accompanying with the flow separation/stall on large scale [(60)].

2.6 Design of Large Sized Front Wind Blade

Horizontal axis turbine of a rotor radius "*R*" has a swept area "*A*" simply given by:

$$A = \pi r^2 \tag{2.17}$$

From equations (2.17), the radius of the wind turbine rotor can be estimated from the following equation:

$$r = \sqrt{\frac{P_a}{0.5\rho\pi V^3 C_P}} \tag{2.18}$$

During rotating, the velocities that act on the aerofoil are shown in Fig. 2-22, where *W* is the relative velocity, and the rotational velocity $u = \omega R$, where $\omega = 2\pi N / 60$ is the angular frequency of the rotor. Drag force F_D component acts always in the direction of *W*, while the lift force F_L is always acting perpendicular to F_D. These force components are dependent on the relative velocity acting on the aerofoil *W*, and the angle of attack α. It is assumed that the forces on a blade element can be calculated by means of two-dimensional aerofoil characteristics using the angle of attack determined as shown above. Figure 2-22 also shows all the velocities and forces relative to the blade chord

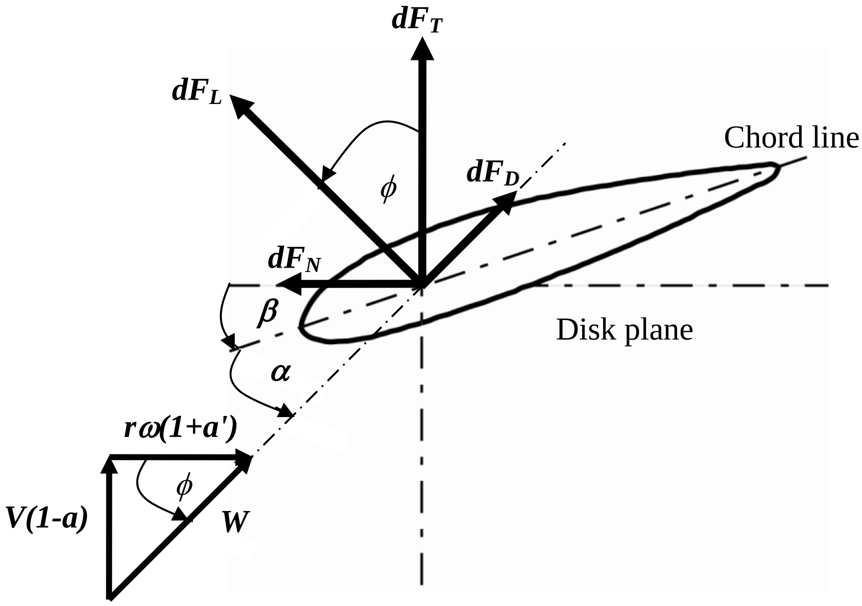


Fig. 2.22 Simple diagram for velocities and forces acting on blade element

line . Resultant relative velocity at the blade can be:

$$W = \sqrt{V^2(1-a)^2 + \omega^2 r^2 (1+a')^2} \tag{2.19}$$

Where *a'* is the tangential induction factor. *W* acts at flow angle ϕ to the plane of rotation, such that

$$\tan\phi = \frac{V(1-a)}{\omega r(1+a')} \tag{2.20}$$

Where β is the blade setting angle, is then given by

$$\beta = \phi - \alpha \tag{2.21}$$

Lift and drag forces can be

$$dF_L = 0.5\rho W^2 C_L c dr \tag{2.22}$$

$$dF_D = 0.5\rho W^2 C_D c dr \qquad (2.23)$$

c is the chord length , while Z is the number of rotor blades

$$c = \frac{8\pi r}{ZC_L}(1-\cos\phi) \text{ [61]} \qquad (2.24)$$

The tip speed ratio λ, is defined as the ratio of the blade tip speed to the free stream wind speed can be:

$$\lambda_F = \frac{\omega r_F}{V} \quad , \quad \lambda_R = \frac{\omega r_R}{V} \qquad (2.25)$$

In the same manner, the local speed ratio is defined as the ratio of the blade speed, at an intermediate radius r, and the free stream wind speed.

$$\lambda_r = \frac{\omega r}{V} \qquad (2.26)$$

So, from equations (2.20), (2.26), the relation between ϕ_r and λ_r can be:

$$\tan\phi_r = \frac{(1+a')}{\lambda_r(1-a)} \qquad (2.27)$$

The thrust force resulting will be

$$dF_N = dF_L \cos\phi + dF_D \sin\phi \qquad (2.28)$$

This thrust force is used in calculating the stresses that act on the tower on the wind power unit. The tangential force resulting will be

$$dF_T = dF_L \sin\phi - dF_D \cos\phi \qquad (2.29)$$

The torque (T) acting on a section will be:

$$dT = 0.5\rho W^2 (C_L \sin\phi - C_D \cos\phi) crdr \qquad (2.30)$$

The mechanical power will be

$$P_a = \omega Z \int_{r_{Hub}}^{r_{Tip}} dT \qquad (2.31)$$

If β_r is changed from the hub to the tip, this will make the blade to be twisted along its length. This will lead to better performance for the blades.

2.6.1 Design point parameters

In this study, the rated conditions for the prototype wind rotors were set as; the output of the generator P_m is 1 kW as the optimum single wind rotor at the wind velocity V= 11 m/s. Taking ρ=1.224 kg/m^3, C_P=0.4, then the radius of the large sized front wind rotor can be:

$$r_F = \sqrt{\frac{1000}{0.5*1.224*\pi*(11)^3*0.4}} = 1\text{m}$$

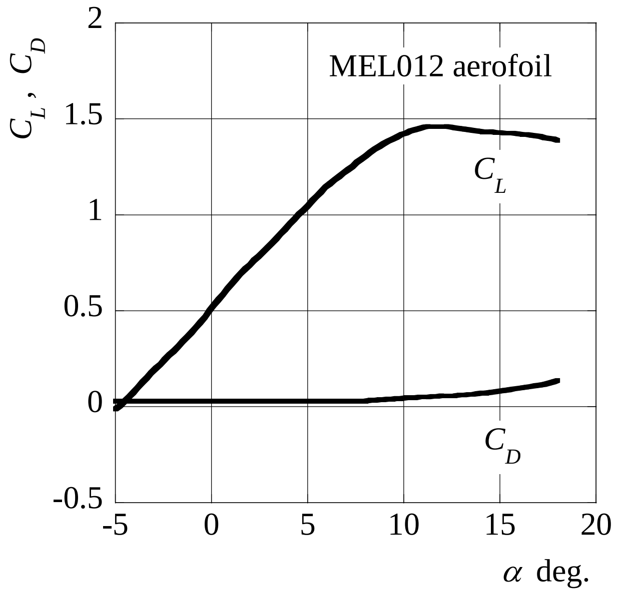


Fig. 2-23 Drag and lift coefficients against the attack angle

Or the diameter of the front wind rotor d_F=2m. The hub diameter was chosen as 290mm to suit the size of wind generator. An aerofoil of MEL012 was chosen for the design of the prototype wind rotor blades used in the experiments. Figure 2-23 shows the drag and lift coefficients C_D and C_L against the angle of attack α for MEL012 aerofoil. The angle of attack giving the maximum C_L is α=11 degrees, but the angle α=8 degrees was chosen as the design condition irrespective of the radial position, so as to avoid the flow stall on a large scale at the lower rotational speed when the rotational speed decreases unexpectedly. Axial distance l_{axs} between both wind rotor twist centers is tentatively chosen as l_{axs} 160mm. The dimensions d_R and l_{axs} were not optimized yet at this stage, though these may affect more or less not only the output but also the rotational behaviors of the wind rotors.

At the design point, the wind velocity was set at V=8 m/s in consideration of the Japanese wind circumstances. The rotational speed of the front and the rear wind rotors are N_F=400 min^{-1} and N_R=-500 min^{-1}. The rotational torque T_F=-T_R= 4.78 N-m was determined so as to get the output P=450 W, at the front and the rear tip speed ratios λ_F =λ_R =7. The blade number of the front wind rotors is 3.

2.6.2 Procedure of design using Blade Element Momentum Model

Now all necessary equations for the Blade Element Momentum model have been

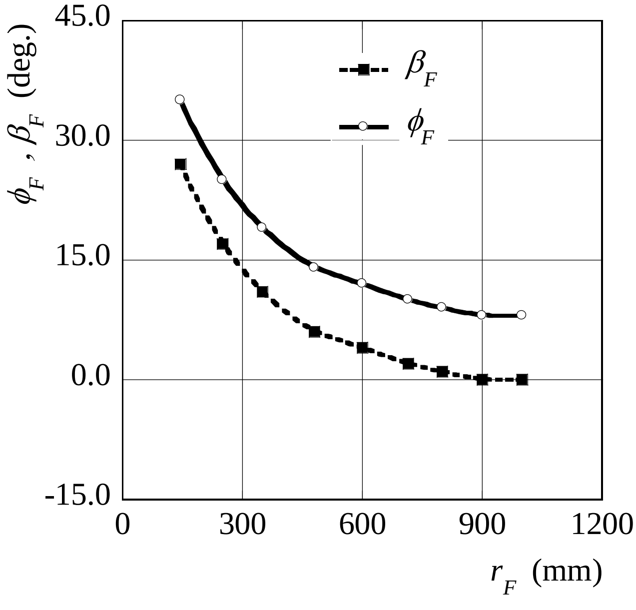


Fig. 2-24 Flow, and twist angles of front wind rotor

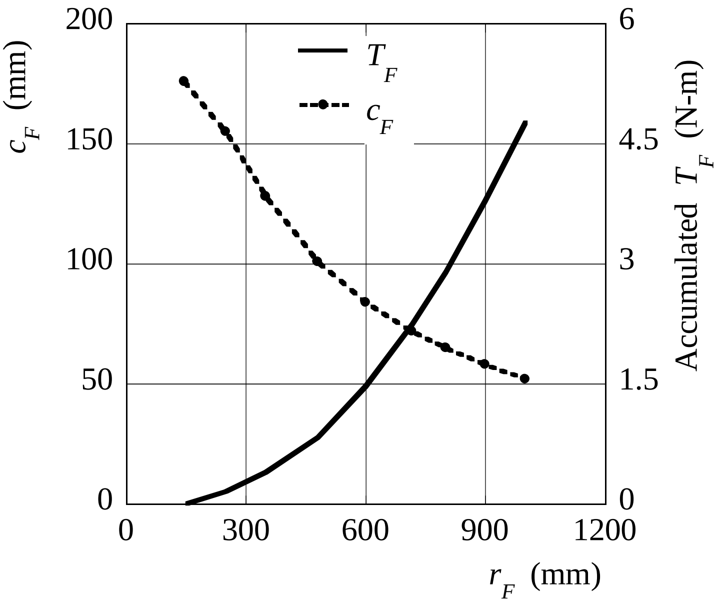


Fig. 2-25 Chord length and accumulated torque of front wind rotor

derived and the algorithm can be summarized as the 8 steps below. First, the blade is divided into several elements from the hub to the tip. All these different control elements are assumed to be independent, so that each strip can be treated separately. The total torque and power acting on one blade are to be equal to the summation of torques and powers of all elements of the blade. Assuming that values of input parameters are given such as that the radius at the tip r_{Tip}, the hub radius r_{Hub}, V, α and C_L, C_D, rotor speed N, then simply the following algorithm is applied.

Step 1. Divide the blade into a number of elements "*n*".

Step 2. Initialize a and a', typically $a = 1/3$, $a' = 0$.

Step 3. Compute the flow angle ϕ for each element using equation (2.20).

Step 4. Compute the blade twist angle β using equation (2.21).

Step 5. Compute the chord length c from equation (2.24)

Step 6. Compute dT as a function in c from equation (2.30).

Step 7. Calculate the mechanical power P_a using equation (2.31).

Figure 2-24 shows the flow angle ϕ_F, and the blade twist angle β_F, while Fig. 2-25 shows the chord length and the accumulated torque T_F, designed by the help of the above procedures. Figure 2-26 shows the profile of the front wind rotor previously designed.

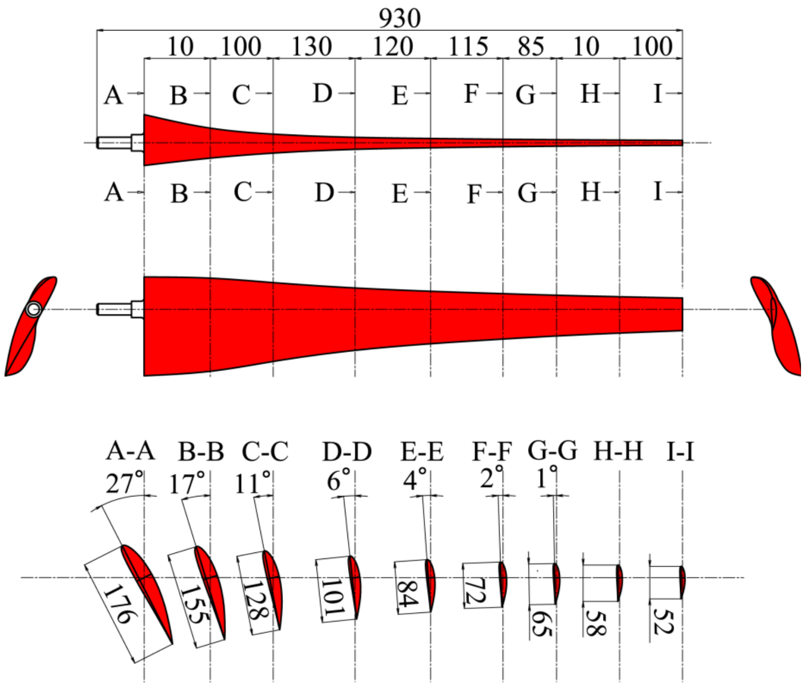
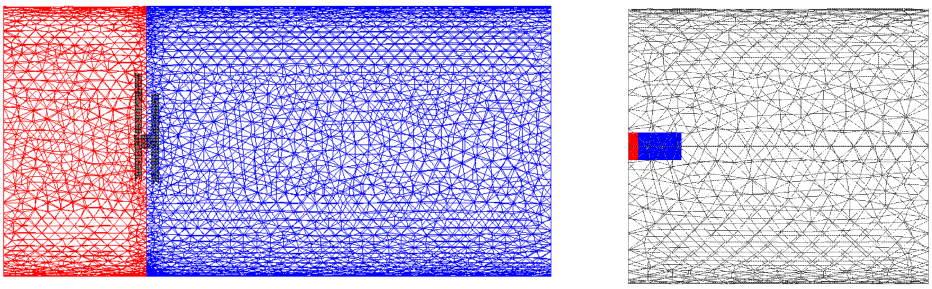


Fig. 2-26 Front wind rotor blade



(a) Fields close to the rotors (region I) (b) Fields surrounding region I (region II)

Fig. 2-27 Fields of the flow simulation with grid generation

2.7 Rear Blade Design

The diameter of the rear wind rotor was tentatively chosen as d_R=1.33m, and number of blades Z_R=5. The counter-rotational torque of the rear wind rotor must coincide with the rotational torque of the front wind rotor designed above, but the

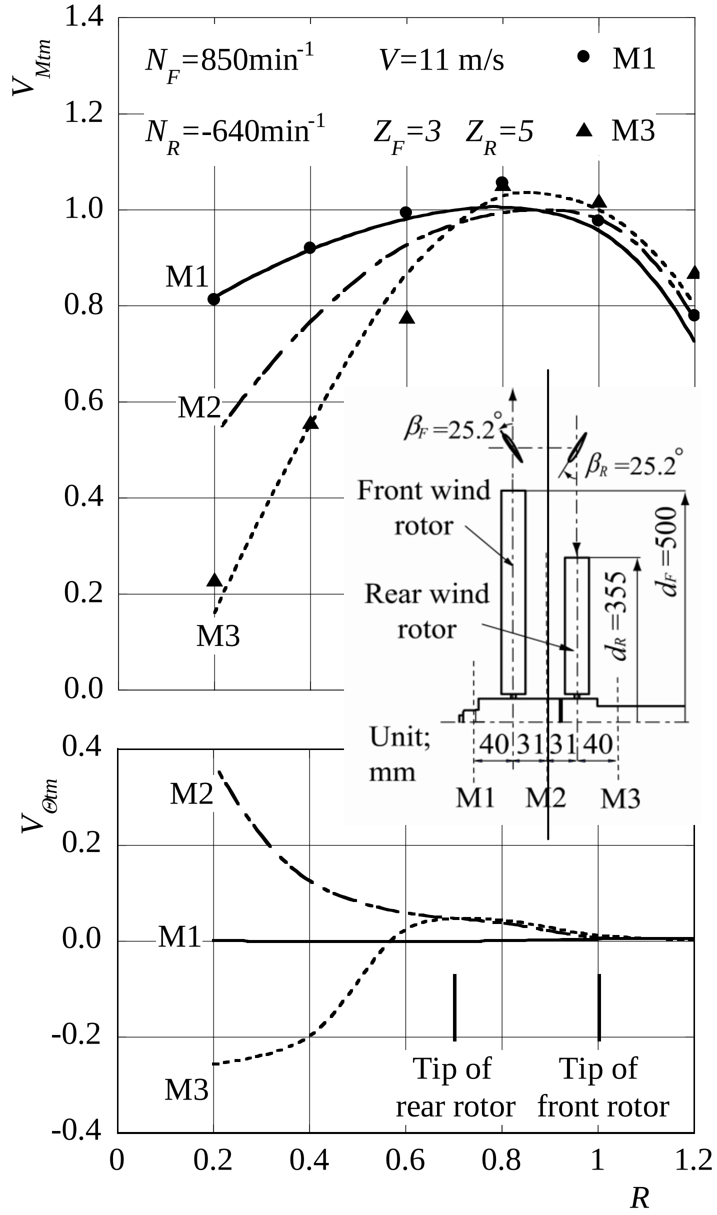


Fig. 2-28 Flow around the tentative tandem wind rotors

convenient design procedures for the rear blade interacting with the front wind rotor is yet not known. It is not easy to determine the profile of the rear wind rotor without knowing the inlet flow conditions of the rear wind rotor. Therefore, the trail was achieved by simulation using CFD.

2.7.1 Simulation using CFD

The flow around the front wind rotor was simulated by the commercial CFD code CFX-10 with k-ε turbulent model, to get the inlet flow condition of the rear wind rotor.

In the simulation, the cylindrical field was set in 20d_F in the radial direction, and was divided into two domains. One is the rotational domain surrounding the wind rotor with 80,668 tetra-type elements (0.5 mm on the blade surface) and 6,294 prism-type elements, which was in 2d_F in the radial direction, 1d_F upstream and 3d_F downstream of the rotor. The other is the stationary domain with 799,060 prism-type elements surrounding the rotational domain, as shown in Fig. 2-27). The flow around the tentative tandem wind rotors with two dimensional blades was simulated in a trial by the above code and is shown in Fig. (2.28) accompanied with the plotted experimental results, where V_{Mtm} and $V_{\Theta tm}$ are the axial and the swirling velocity components divided by the inlet wind velocity V, R is the dimensionless radius divided by $d_F/2$, and the sections M1-M3 and the blade profile are also given in the figure. It can be confirmed that the above code can predict roughly the actual axial velocity.

2.7.2 Comparison between experimental and simulated data

The flow around the front wind rotor equipped with the blades shown in Fig. (2.28) was simulated by the above code. Figure (2.29) shows the relative flow angles measured from the tangential direction at the downstream of the front wind rotor, where

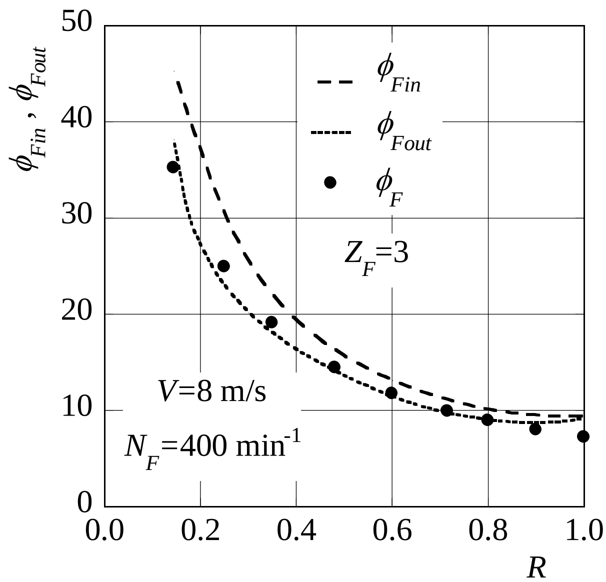


Fig. 2-29 Relative flow angles measured from the tangential direction

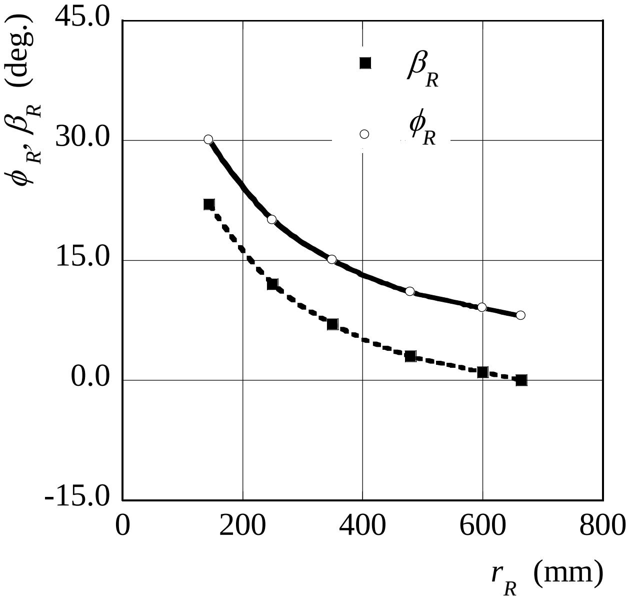


Fig. 2-30 Flow, and twist angles of rear wind rotor

ϕ_{Fin} and ϕ_{Fout} are the simulated inlet and outlet relative flow angles, ϕ_F is the angle determined above by the equation (2.20) at each radial position of the front blade. The angle ϕ_F is close to ϕ_{Fout}, that is, ϕ_F may give the outlet flow angle. Accordingly, the rear rotational torque, namely angular momentum change, was determined with the simulated outlet flow angle of the front wind rotor, which is corresponding to the inlet

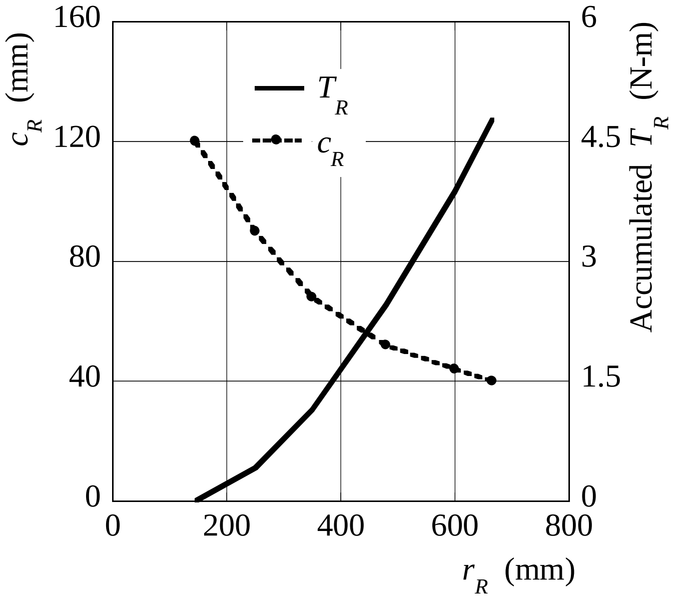


Fig. 2-31 Chord length and accumulated torque of rear wind rotor

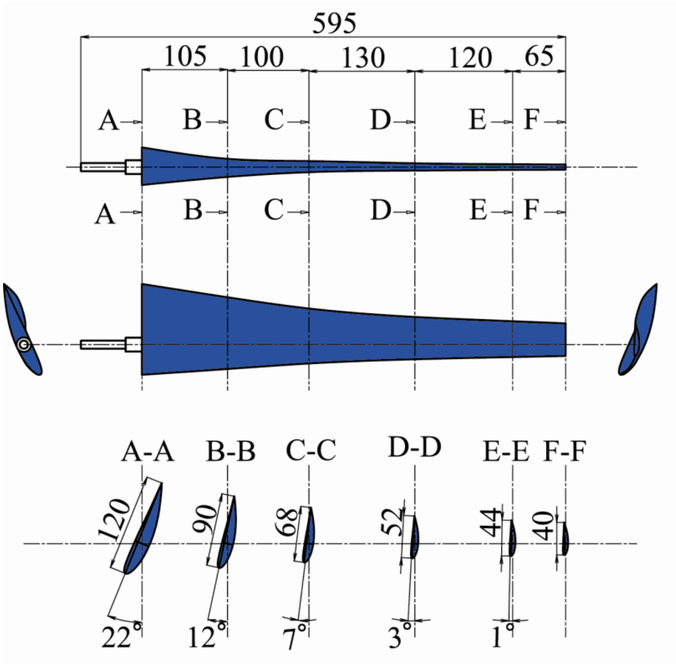


Fig. 2-32 rear wind rotor blade

flow angle of the rear wind rotor, and the outlet flow angle of the rear wind rotor predicted by the equation (2.20).

Figure 2-30 shows the flow angle ϕ_R, and the blade twist angle $\beta_{R,}$ while Fig. 2-31 shows the accumulated torque T_R. Figure 2-32 shows the profile of the rear wind rotor previously designed. The chord was derived from the equation (2.24) and the blade setting angle with angle of attack α=11 degrees is β_R=0 degree at the blade tip.

Conclusions

Experiments were done to verify the superior operations of the unique wind power unit. Bench tests were done on both unique wind turbine generators, namely the doubly fed induction generator with double rotational armatures, and the permanent magnet synchronous generator with double rotational armatures. Front and rear wind rotors were designed.

Concerning the doubly fed induction generator with double rotational armatures, the following points were noticed:

1. In order to keep the output frequency constant at f_1=60 Hz, , its found that the input frequency f_2 is inversely proportional with the relative rotational speed between tandem wind rotors N_T.
2. To keep the output voltage constant at E_1=200V, the input voltage E_2 will not depend only on N_T but also on P_1, namely the load
3. The input P_2 comes to be negative at the higher rotational speed than the synchronous speed N_T=900 min, which means adding the power to the output.
4. When keeping the output voltage at 200V, and the output frequency constant at 60 Hz, it was shown that the output increases with the increase of the induced voltage E at the same I, while E is proportional to the relative rotational speed N_T and I determine the rotational torque.

Preparations were done to start the field tests on the wind power unit consisting of the permanent magnet synchronous generator with double rotational armatures, equipped with the tandem wind rotor mentioned before. This synchronous generator was used successfully in hydroelectric turbines. The main results are as following

5. It was verified experimentally that the torques of the inner and the outer armatures are equal and counter balance (T_{GR}=T_{GF}).

Concerning the design of the tandem wind rotors, the following points were noticed:

6. The optimum number of blades for the front wind rotor is three, while for the rear wind rotor is five.
7. Tandem wind rotors of MEL012 profile were designed and manufactured using basic aerodynamic theories, mainly Blade Element Momentum model.
8. The diameter of the large sized front wind rotor was 2m , while the diameter of the small sized rear wind rotor was 1.33m.

Chapter 3

Wind Power Unit Field Tests

The next step after preparing the unique type wind power generators with double rotational armatures, and designing and manufacturing the tandem wind rotors was to examine the performance of the wind power unit in the field. Experiments were first done using the doubly fed induction generator with double rotational armatures, equipped with the previously designed tandem wind rotors. The field test site was located on a hill close to the seashore of Wakamatsu city in Japan.

3.1 Site wind circumstances

First, the wind intensities and directions were measured at the site, so that to study the wind circumstances before making the experiments on the wind power unit. Figure 3-1 shows the daily averaged velocity in magnitude and direction at the field test site. The season at this time had comparatively good wind circumstances for generating the

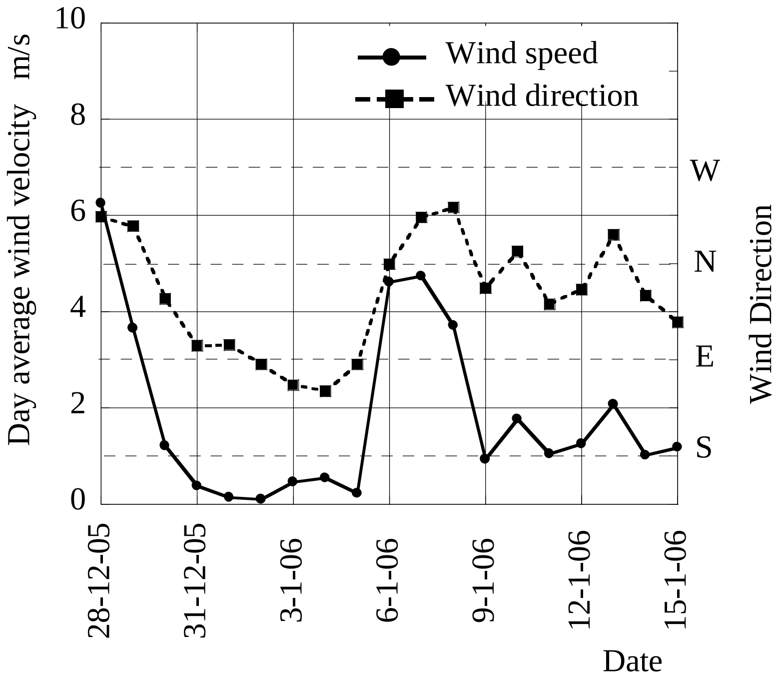


Fig. 3-1 Daily averaged wind velocity at the field

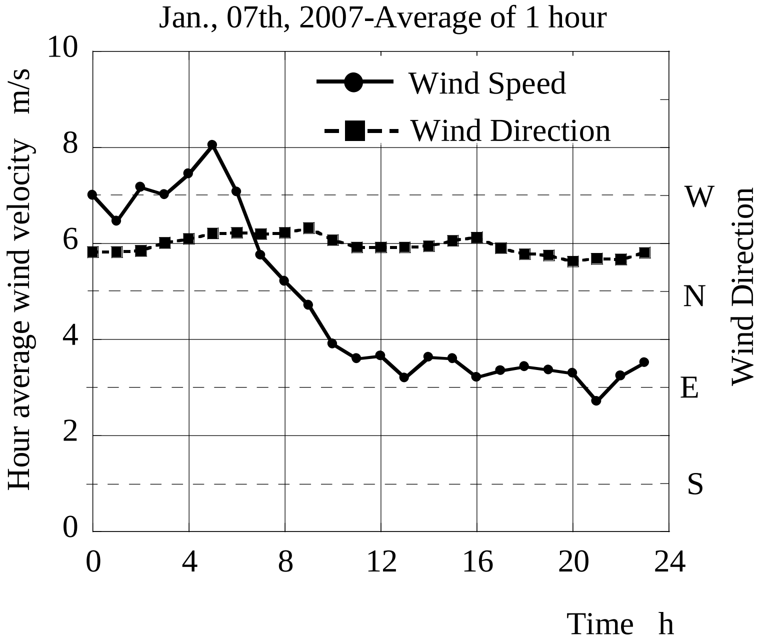


Fig. 3-2 Hourly averaged wind velocity at the field

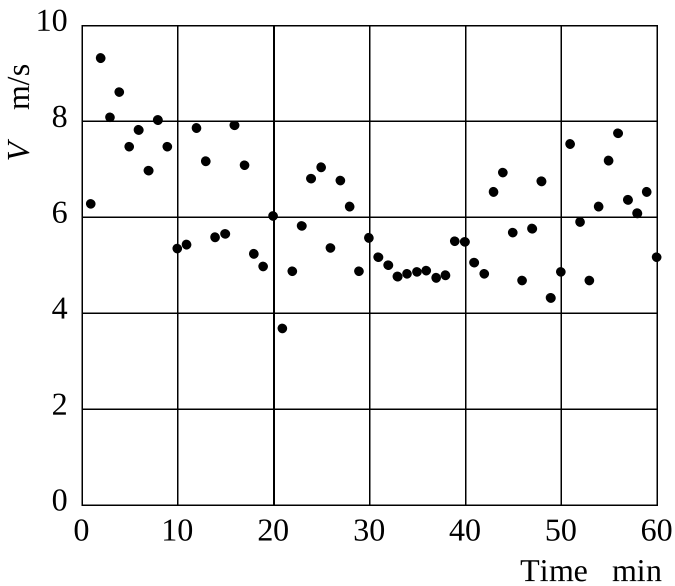


Fig. 3-3 Momentary wind velocity in the field

power, but unfortunately both the magnitude and direction of the wind velocity were varied from day to day. Figure 3-2 shows the hour averaged wind velocity on January, the 7th, 2007 where there was comparatively strong wind. The wind velocity also was varied from hour to hour, but fortunately the northeasterly wind was nearly constant in magnitude and directions. Figure 3-3 shows one of the momentary wind velocity *V* that

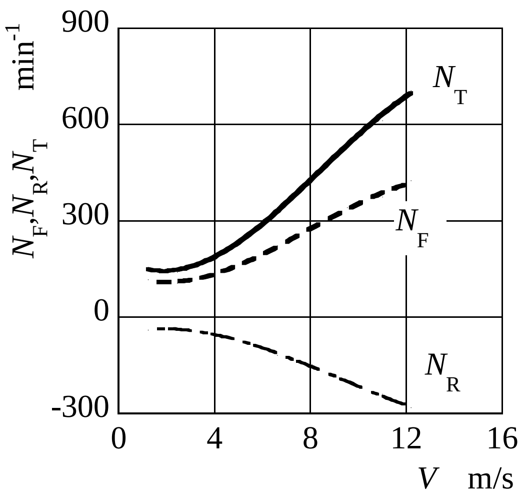


Fig. 3-4 Rotational speeds against wind velocity

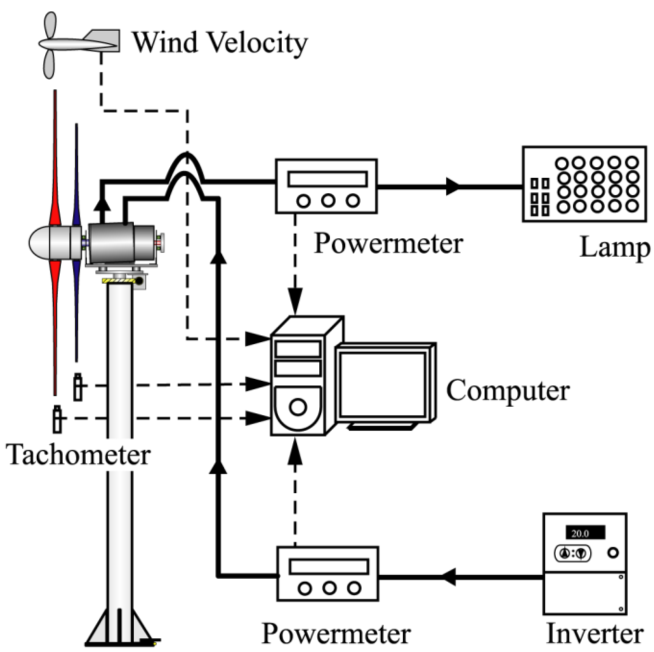


Fig. 3-5 General view of the field test circuit

was averaged for one minute at the wind rotor position. The rotational speeds of both wind rotors were effected markedly by the turbulent and/or gust conditions. The rotational speeds against the wind velocity are shown in Fig. 3-4 accompanying with the velocity. The front and the rear wind rotor speeds increase with the increase of the wind velocity, however, both wind rotors did not reach the designed rotational speed, that is N_F=400 min^{-1} and N_R=500 min^{-1} at V=8 m/s. The reason for that may be

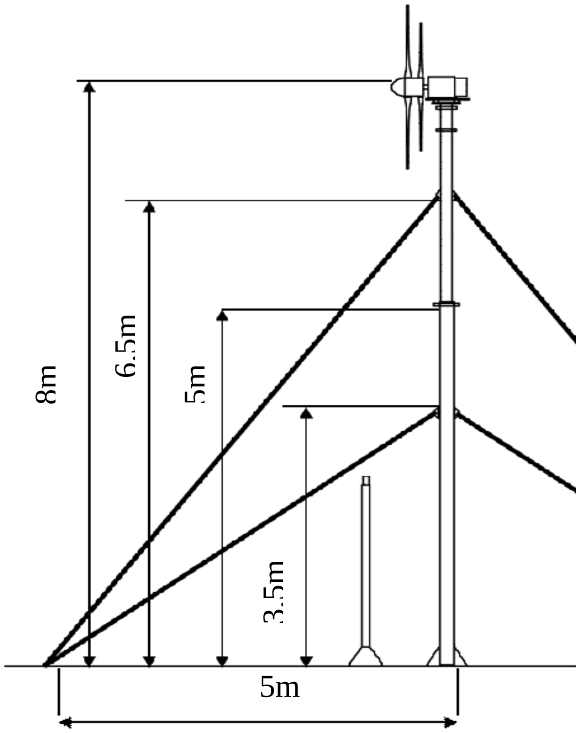


Fig. 3-6 Tower dimensions

because the wind rotors can not respond rapidly to the wind velocity due to the large inertia moments due to friction, because the total weight of the unit over the tower is around 175kg including the generator, the rotors and the yaw mechanism.

.

3.2 Control circuit of wind power unit

The wind turbine unit was prepared for making the experiments, as shown in Fig.3-5. Measurements of the operating conditions, and input and data were easily recorded and displayed through a screen, attached to the control panel unit. The unit was mounted on a tower that was made of two cylinders flanged at their ends, and connected to each other through bolts. The tower was supported by guy wires in four directions at a position of 3500mm and 6500mm from ground, as shown in Fig. 3-6. These guy wires are also used to absorb the vibrations of the wind power unit, and to help in erecting and lowering the tower, as shown in Fig. 3-7. The full length of the tower is 8000mm, and it is divided in two parts at a position of 5000mm from ground. The unit was equipped by

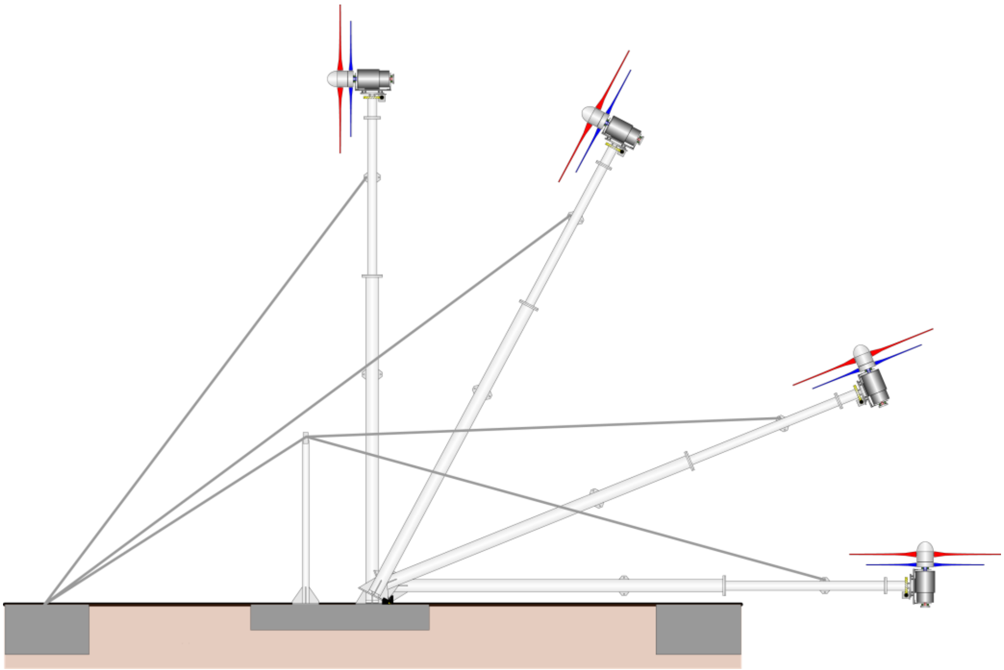


Fig. 3-7 Erecting and lowering the tower and wind power unit using guy wires

a magnetic braking system for safety requirements, and also it is used when it is required to make maintenance for the wind power unit. Also, yaw mechanism was attached to the unit just under the seat of the wind generator to direct the wind power unit at positions where it can get best wind conditions. The motion of the yawing system was done by the help of warm and warm wheel, which permit the unit to rotate 360 degrees around the tower axis as shown in Fig. 3-8. This rotation was done manually using switches that can control the motion. The future plan is to attach a wind measuring device that can detect the speed and direction of the wind then direct the wind power unit automatically to the proper direction.

Although the site was encouraging, but in general, the Japanese wind is weak and fluctuating, while higher wind velocities were needed to test the wind power unit in different wind circumstances. For this reason, the wind power unit was mounted on a moving truck to stimulate better wind conditions, and to simulate the work of the wind tunnel through making the experiments under different wind velocities. To make these experiments, another new location was selected for the truck travel.

3.3 Field test location

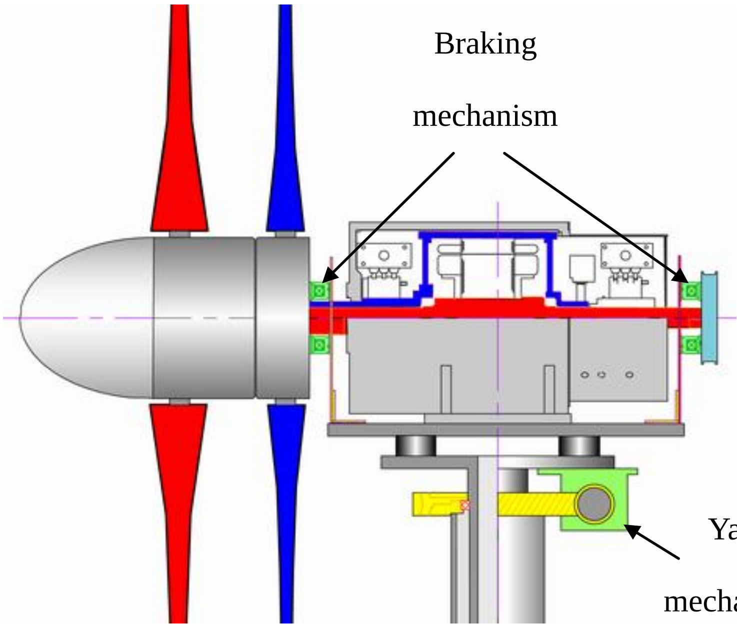


Fig. 3-8 Yaw and braking mechanisms

Site of the tests using the pick-up truck was chosen this time just beside the see-shore of Wakamatsu ward, where there are 10 huge wind turbine units working effectively and connected to the electric grid. Two straight roads, each of them is of about 1.5 Km were used in the experiments. One road was located in the north-south direction, while the other one was located at the east-west direction. The wind at both roads was calm and its direction was nearly constant, that is, the site was suitable for making the experiments using the pick-up type truck which needed to be driven straightly at constant speed, as shown in Fig. 3-9. The site has a comparatively high wind velocity, at nearly a constant magnitude and direction. Also, safety precautions were put in mind when choosing the timing of the tests.

Fig. 3.9 Straight road of 1.5km used in the tests

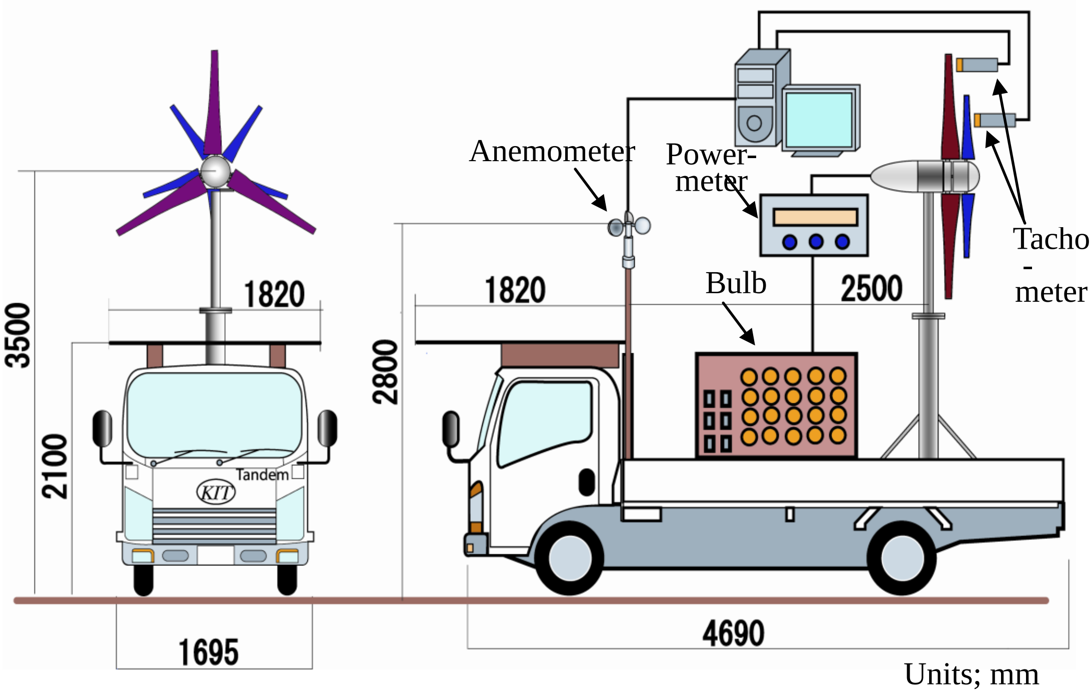


Fig. 3-10 Field experiments on the pick-up type truck

Fig. 3-11 Cup-type anemometer

Fig. 3-12 Laser-type tachometer

Most of the experiments were done at holidays (Saturday, and Sunday).

3.4 Test equipments and measuring tools:

Experiment apparatus was equipped with a cup-type anemometer for measuring the wind velocity. The anemometer was fixed to the body of the truck at relatively reasonable height, as shown in Figs. 3-10, 3-11. Laser type tachometers were adjusted just over the shafts of the large sized and the small sized tandem wind rotors so that to

Inner armature

Outer armature

Fig. 3-13 Measurements of rotational speeds of double rotational armatures

measure their rotational speeds, as shown in Figs. 3-12, and 3-13. Output of the wind power unit was consumed/absorbed through sets of bulbs that can give different resistances representing the applied load applied on the wind power unit. These resistances are connected to the circuit using on/off switches, which can control the values of the total resistances. The resistances depend mainly on the induced voltage and the induced electric current affecting the temperature of the filament. Therefore, these resistances were replaced by standard power at 100 V bulbs as an indication for the temporal load, as shown in Fig 3-14. All these input and output data were automatically accumulated and stored in a personal computer through software which records all these data every one second. The data sheet of the software includes the rotational speeds of the large sized and the

Fig. 3-14 Bulb loads

Fig. 3-15 Input and output data recording

small sized wind rotors, the relative rotational speed between them, the wind velocity, the induced current, the induced voltage, and the output power of the wind power unit, as shown in Fig. 3-15.

The pick-up truck used was of 2ton loading capacity, and its space was so convenient not only to carry the experimental equipments and testing tools, but also it could have convenient space for the operator to set, notice, and adjust the behavior of the wind power unit during the movement of the pick up truck, as was shown in Fig. 3-10. The movement of the truck was simulating the work of the wind tunnel in the bench tests. The wind velocity was controlled by controlling the driving speed of the truck, so that the driver of the truck is always in contact with the observer/operator who sits with the wind power unit to notice its behavior and to ensure achieving the required input data during the experiments. These experiments were done using two different crossed roads as mentioned previously, the wind in one of them blows at it from the west/east directions while at the other road the wind blows from the south/north directions. The road is decided according to its wind conditions which can give better experimental results.

3.5 Experimental Procedures:

The experiments were done through controlling three main parameters, which are the load, the blade setting angles, and the wind velocity. The desirable load values can be set using the on/off switches, the blade setting angles of the front and the rear wind rotors are set manually in each experiment, while the wind velocity can be simulated by adjusting the truck speed. At first, the truck speed increases gradually in a straight line till the anemometer measures the required wind velocity. At this instant the truck is driven at a constant speed along the straight rode till few meters before the end of the stroke, and then the truck decelerates and stops. Always there is a continuous feedback from the observer/operator who is sitting, watching and operating the different input data and the truck driver. The car can be driven for nearly 1.5km along a straight line in each stroke. So, during each stroke, the truck passes though three main periods, which are the acceleration period, the steady state period, then the deceleration period. Figure (3.16) shows one of the rotational speeds of the front and the rear wind rotors N_F, N_R, and the wind velocity V accumulated from start to stop of the truck. Data of input and

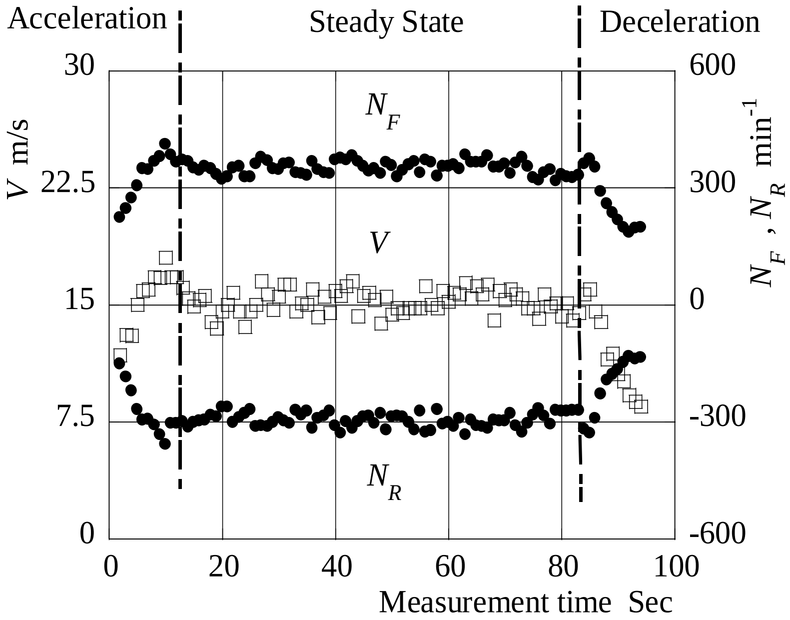
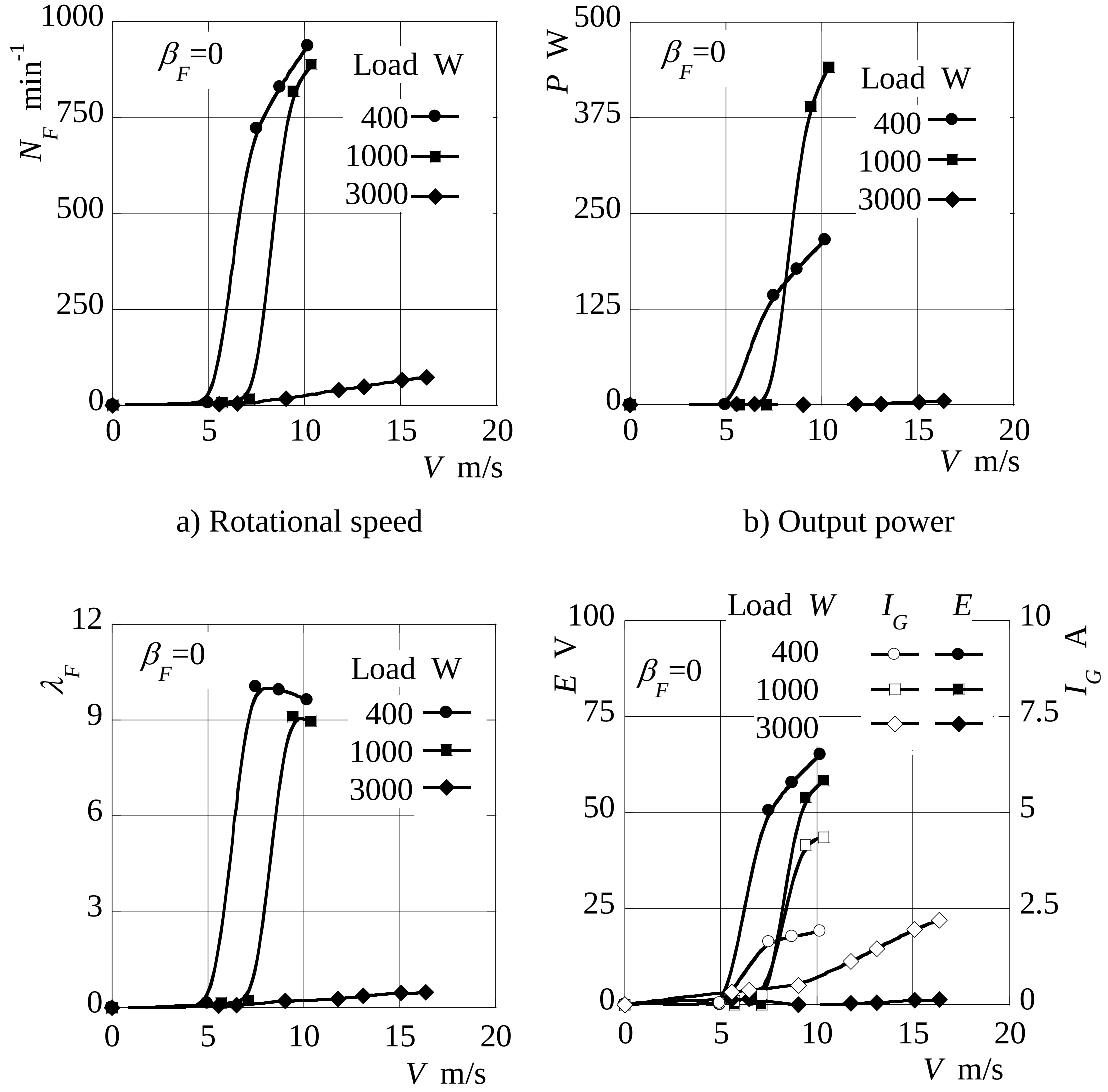


Fig. 3.16 Accumulated rotational speeds through measurement time

output parameters are stored automatically in the PC every one second, while data of every stroke is labeled manually and stored in the computer. After finishing all the strokes, the data recorded inside these files are filtered so that the data corresponding to the acceleration and deceleration of the truck are excluded in order to get the results at the steady state flow conditions.

Every time input data is changed while experiment is repeated and input and output data are recorded. For example, blade setting angles of both tandem wind rotors are set at 10 degrees, while load is set to a value of 423W, and the truck moves till its speed stimulate a wind velocity of 4m/s. The results of this experiment are recorded. The experiment is done again with the same previous conditions except changing the wind velocity to be 5m/s, and again the data is recorded. Every time the velocity of the wind is changed while the other data are kept constant until all the required wind velocities are fulfilled. All previous data are filtered, stored and plotted.

Again, the experiment is done while keeping the blade setting angle of the front wind rotor at 10 degrees, and the load at 423W, while changing the blade setting angle of the



a) Rotational speed

b) Output power

c) Tip speed ratio

d) Voltage and current

Fig. 3.17 Performances of single wind rotor (Front blade)

rear wind blade to 20 degrees. These values are kept constant while changing the wind velocity through adjusting the speed of the truck, as was done before. So these experiments are repeated with changing the values of the small sized rear wind rotor, while keeping the rest of the parameters constant, while changing the wind velocity. After changing all blade setting angles, the experiments are repeated while changing the load and the wind velocity while keeping other parameters constant, and so on.

All previous experiments which were done on the wind power unit were used for the case of single wind rotor using the large sized front wind rotor only, and also for the case of tandem wind rotors, so that to study the effect and behavior of the small sized rear wind rotor on the performance of the unique wind power unit.

3.6 Performances of Single Wind Rotor (Front Blades)

To study the performances of the front wind rotor as a single stage, the rear wind rotor was detached from the unit while the shaft attached to inner armature was locked. The blade setting angle of the front rotor was set at β_F=0 degree which is corresponding to the design value. Experiments were done using loads of values 400w, 1000w, and 3000w.

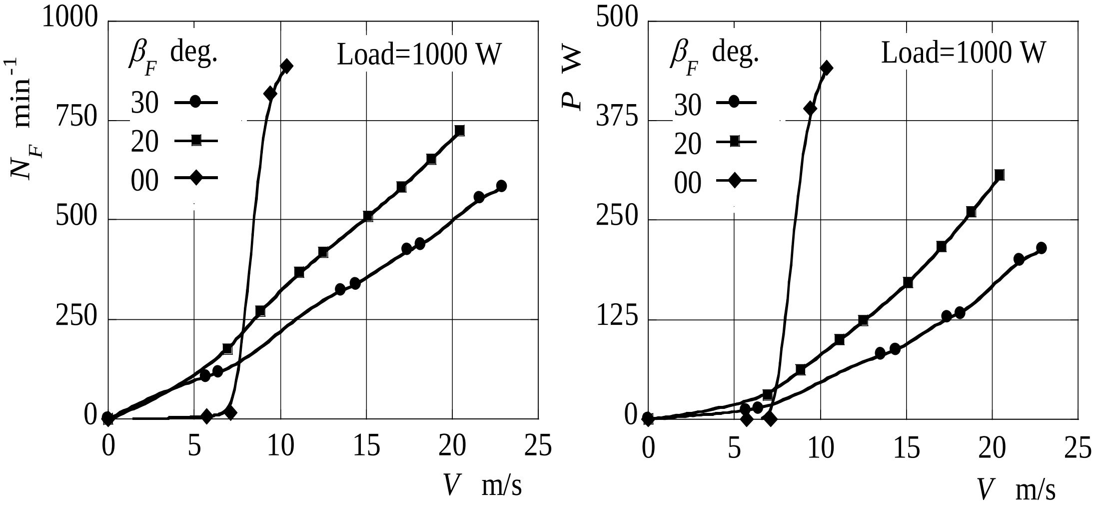
3.6.1 Effect of load:

Performances of single wind rotor (front blade) are shown in Fig. (3.17). Figure (3.17-a) shows the rotational speed of the single wind rotor against the wind velocity. It can be obviously seen that the wind rotor hardly rotates in the lower wind velocity *V* while keeping the load constant, but begins to rotate suddenly at *V* higher than 5m/s under the load lower than 1kW, where the experiments were stopped at *V* higher than 11 m/s to avoid the abnormal rotation. Although the wind rotor at load of value 3000W permitted higher wind velocities, but it continued o rotate at low rotational speed.

The output *P* was also increased suddenly in accompanying with the increase of the relative rotational speed of the wind rotor, as shown in 3-17 (b). Figure 3-17 (c) shows the blade tip speed ratio against the wind velocity. It is shown obviously that the tip speed ratio is affected by the rotational speed of the single wind rotor. The values of λ were high at low load values, while were so low at high load values. Figure (3.17-d) shows the induced voltage and induced current against the wind velocity. These values of induced voltage and induced current are clearly affected by the wind velocity.

3.6.2 Effect of Blade setting angle:

The effects of the setting angle β_F on the rotational speed are shown in Fig. 3-18. β_F has taken the values of 0degrees, 20degrees, and 30degrees, while the value of the load was kept constant at 1000w. From this figure, it is clearly shown that the rotational



a) Rotational speed b) Output

Fig. 3.18 Effect of the blade setting angle on the performances (Front blade)

speed N_F increases gradually with the increase of the wind velocity V, while the value of β_F=20degrees gave better rotational speed performance, because the experiment was stopped below a wind velocity of 11m/s for safety of the experiment. Figure 3-18 shows that the value of β_F=20degrees may be suitable for the load=1000 W in the measured data, because the output P also increases gradually with the increase of the wind velocity V, however, it never reached the generator capacity because of the very slow rotational speed. The output P at the designed β_F=0 degree may reach the required capacity.

Through these previous experiments, it was shown that for a single wind rotor, it hardly rotated in the lower wind velocity V while keeping the constant load, but began to rotate suddenly at V higher than 5m/s under the load lower than 1kW. The former may be caused not only by the mechanical torque and the magnetic force, but also by the flow stall on large scale due to the excessive attack angle. At sudden increase of the rotational speed N_F, the output P also increased suddenly in accompanying with the increase of induced voltage E and the induced electric current I. At the larger load 3kW, however, the wind rotor speed N_F increased gradually with the increase of V, but N_F was very low and the output P is tiny. These data suggests that there is an optimum load suitable for the wind velocity.

When wind rotor rotates, it extracts power from wind and generates a forward torque that rotates the armatures of the generator. Continuously, there will be a back torque resisting this rotation. When the forward and back torques becomes the same, this will lead to an equilibrium condition. At different speeds, there will be particular generated torques, and there will be also resisting torques, which will be given by the loads applied on the electrical generator. If the wind rotor is rotating the armatures of the generator, then if there is no load the generator will rotate with high speed but because there is no back torque resisting its motion. The moment at start loading the generator, means that power generated from the mechanical side due to the rotation of the wind rotor will feel that something is trying to slow it down. For every wind power unit, there is a curve describes the characteristic of the load torque. If this wind turbine is supplying energy to some kind of load, then it will have its own T versus N characteristics against this load. The wind power unit always operates properly when the load torque is overcome by the generated torque, and this always happens at the rated wind velocity of the wind power unit.

Through previous results, it was shown that for single wind rotor, it hardly rotates at lower wind velocities V while keeping the load constant, but begins to rotate suddenly at V higher than 5m/s under the load lower than 1kW, where the experiments were stopped at V higher than 11 m/s (λ_F higher than designed 7) to avoid the abnormal rotation. The former may be caused not only by the mechanical torque and the magnetic force, but also by the flow stall on large scale due to the excessive attack angle. At a sudden increase of the rotational speed N_F, the output P also increases suddenly in accompanying with the increase of induced voltage E and the induced electric current I. At the larger load 3kW, however, the wind rotor speed N_F increases gradually with the increase of V, but N_F is very low and the output P is tiny. These data suggest that there is an optimum load suitable for the wind velocity.

When a wind rotor rotates, it extracts power from wind. During rotation, there will be a back torque resisting this rotation. When the forward and back torques is the same, this will lead to equilibrium condition. At different speeds, there will be particular generated torques, and there will be also load torques, which will be given by the electrical generator. Suppose that the wind rotor is rotating the armatures of the generator. So, if the there is no load, then the generator will not give any back torque. The moment we start loading the generator, means that power goes in the mechanical side, then rotors will feel that something is trying to slow them down, and that they have to work against it. This is what meant by the back torque every time power is generated and actually converted into the electric energy. For every wind power unit, there is a curve describes the characteristic of the load torque. If this wind turbine is supplying energy to some kind of load, then it will have its own *T* versus *N* characteristics against this load. The wind power unit always operates where the load torque is overcome by the generated torque, and this always happens over specific wind velocities. These wind velocity together with the applied load may suggest particular suitable blade setting angles.

3.7 Performances of Tandem Wind Rotors

After studying the effect of wind velocity and the blade setting angle at the single rotor, the rear wind rotor was attached to study its effect on the performance of the unit as a tandem with the front wind rotor. The blade setting angles were changed from 0 degrees to 30 degrees through an increment of 10 degrees for each step on each wind rotor. For example, at the beginning, the front blade setting angle is adjusted to 10 degrees, and the same is done to the rear blade setting angle, then these values remain the same during moving with different wind velocities. In each time load is changed to see its effect. Then experiments are repeated again and again, while changing only one parameter, and keeping the others constant.

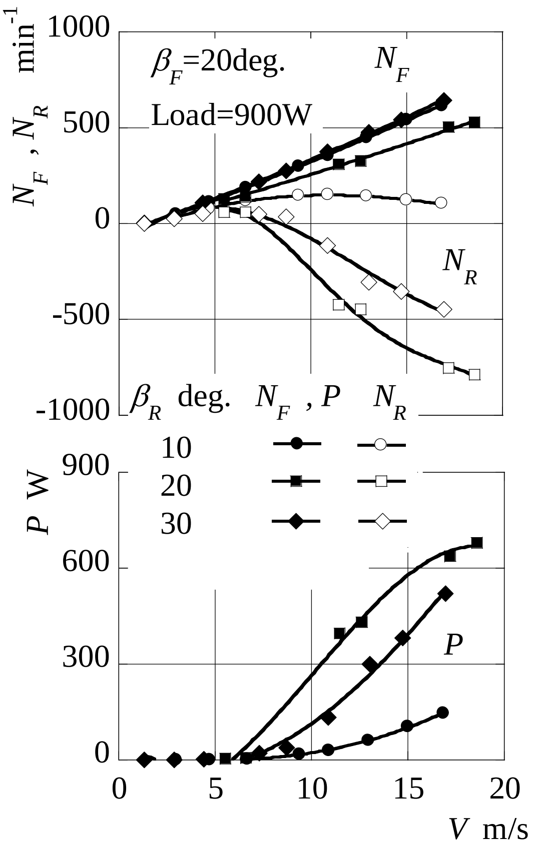


Fig. 3.19 Effect of the rear blade setting angle on the performances

3.7.1 Effect of blade setting angles

The effects of the rear blade setting angle β_R on the performances are shown

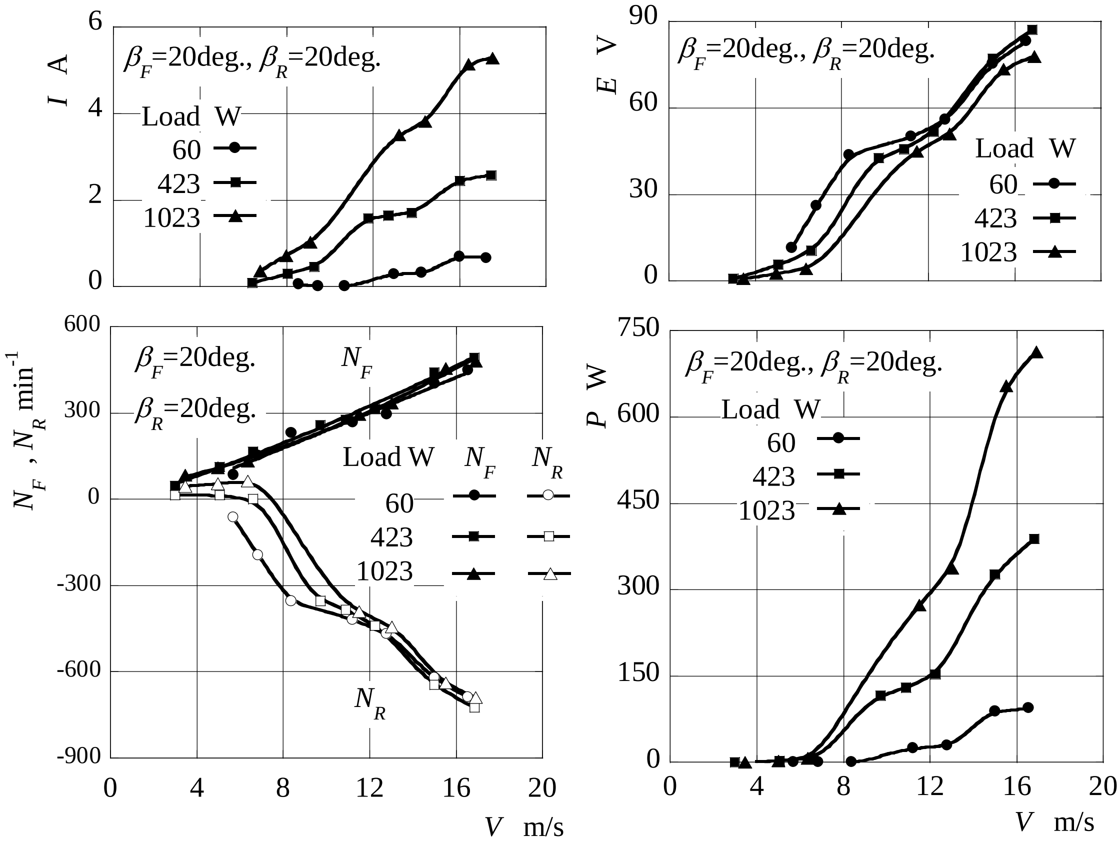


Fig. 3-20 Effect of the bulb load on the operating conditions

in Fig. 3-19 in keeping the front blade setting angle β_F=20 degrees and the load 900 W. At these operating conditions, the rear wind rotor never counter-rotates against the front wind rotor at the lower wind velocity *V*. With the increase of the wind velocity, the rear wind rotor with β_R larger than 20 degrees begins to counter-rotate successfully, but the rotor with β_R=10 degrees does not change its rotational direction. Figure 3-20 shows the effect of load on the performances with blade setting angles β_F= β_R=20 degrees. The load affects obviously the rotational speed of the rear wind rotor N_R in the lower wind velocity than 12 m/s, but scarcely affects the speed of the front wind rotor N_F irrespective of the wind velocity *V*. Besides, the rear wind rotor counter-rotates at the slower wind velocity with the decrease of the load, namely the magnetic force. The relative rotational speed N_T contributes to the induced voltage *E*, the induced electric current I_G depends on the load, and the output is obtained electrically from $\sqrt{3}EI$, while given mechanically by $T\omega_T$. In the measured data, the operating condition with the load 1023 W gives the higher output *P*.

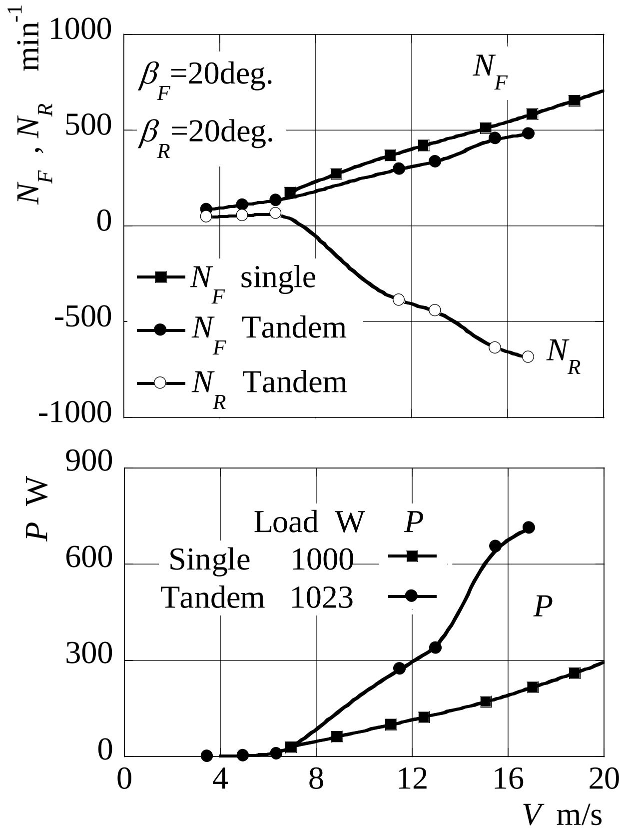


Fig. 3-21 Comparison of the performances between tandem and single wind rotors

3.7.2 Comparison with single wind performances

Figure 3-21 compares the performances of the case of tandem wind rotors with the case of the single wind rotor, though these specifications are not yet optimized. The rotational speed of the front wind rotor N_F is slightly slow due to the interactions from the rear wind rotor, as compared with the single wind rotor. The output of the tandem wind rotors, however, is remarkably higher due to the counter-rotation of the rear wind rotor. The output of the single wind rotor, however, may be higher than that of the prepared tandem wind rotors, if making the increase of the rotational speed free even at higher wind velocity without considering the dangers and the blade setting angle β_F=0 degree.

The rear wind rotor never counter-rotates against the front wind rotor at the lower wind velocity V because not only the rear wind rotor cannot generates the sufficiently counter-rotational torque T_R corresponding to T_F of the front wind rotor but also the outer armature pulls the inner armature by the magnetic force due to the comparatively higher load. With the increase of the wind velocity, the rear wind rotor with β_R larger than 20 degrees begins to counter-rotate successfully, but the rotor with β_R=10 degrees does not change the rotational direction because the rear blade with the larger attack angle cannot generate the fruitful counter-rotational torque due to the flow stall on larger scale. Judging from the counter-rotation expected to this wind turbine unit and the output, the rear wind rotor with β_R=20 degrees may be acceptable in the measured data.

3.8 Trials of Reasonable Operations

As recognized in the above discussions, the performances are affected not only

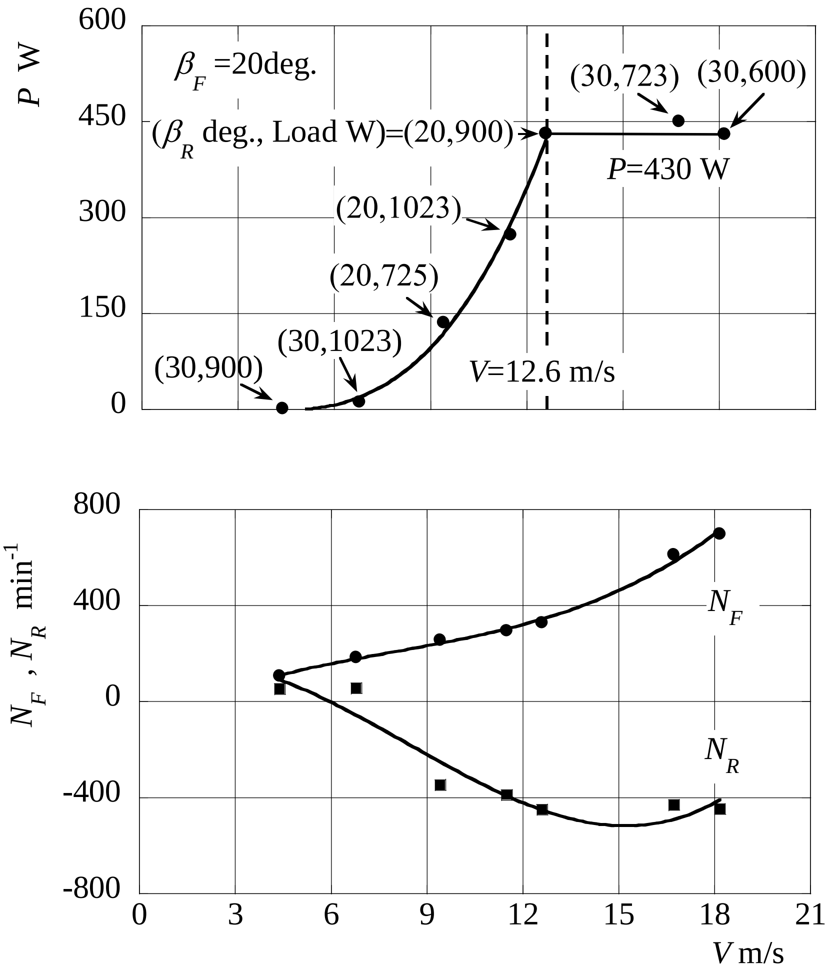


Fig. 3-22 First trail of reasonable operations

by the wind velocity V but also by the blade setting angles β_F, β_R and the bulb load. This wind turbine unit was operated in trail by changing the rear blade setting angle β_R and the load, while keeping the front blade setting angle β_F=20 degrees. The output was kept constant at P=430 W in the wind velocity higher than V=12.6 m/s, and was the aximum at each V in the slower wind velocity. In the trial, the output in the rated

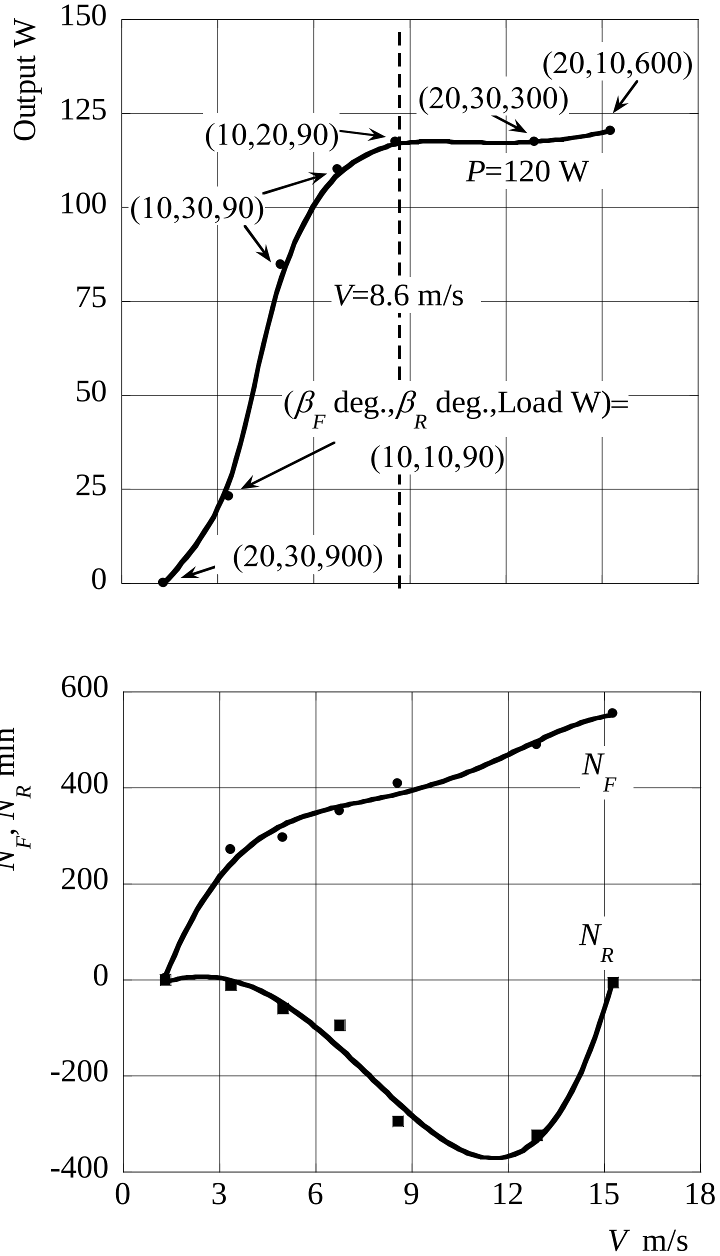


Fig. 3-23 Second trail of reasonable operations

operation was selected as close as possible to the rated power P= 430W in the measured data, and the maximum output was selected in the measured data at each lower wind velocity, because the blade setting angles and the load could not be changed continuously on the truck. Figure 3-22 shows the operating conditions denoted with the selected rear blade setting angle β_R and the load, where the load is not related directly to

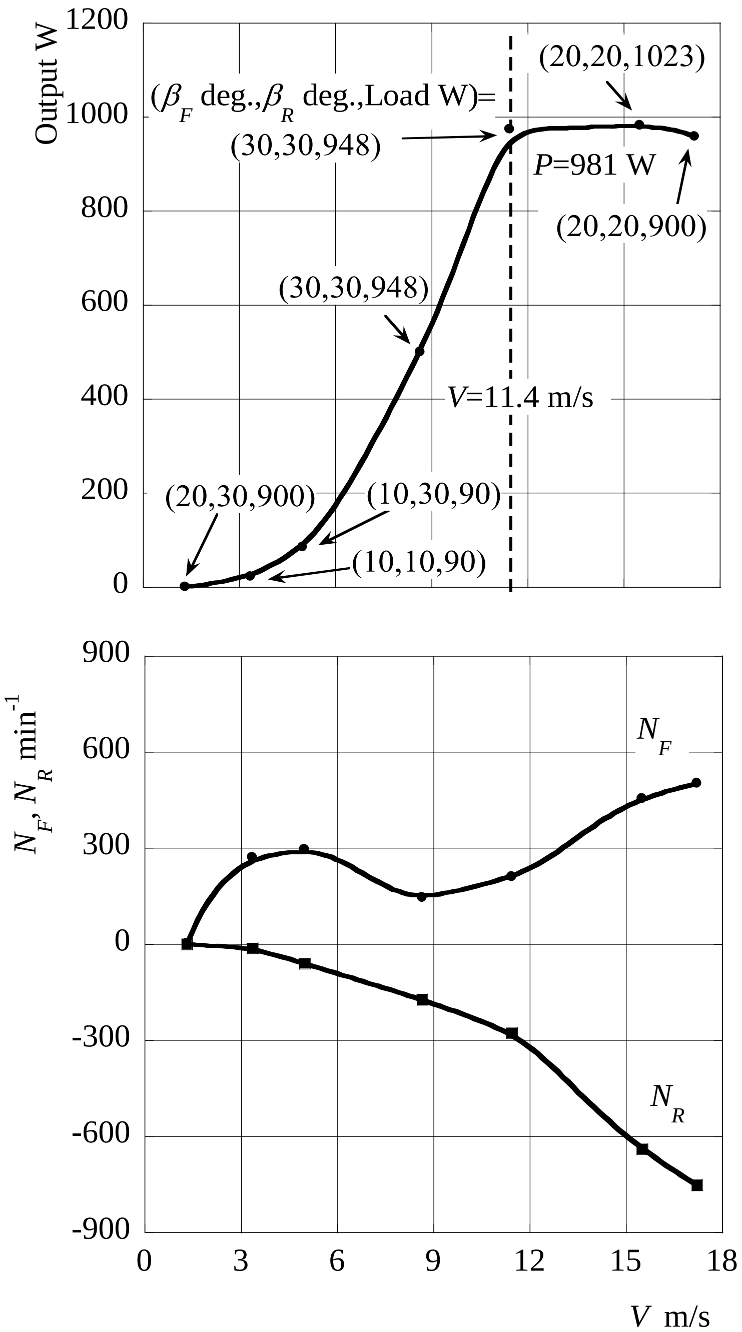


Fig. 3-24 Third trail of reasonable operations

the output because the bulb resistances is changed by the filament temperature as mentioned before. The selected outputs with the rotational speeds are plotted and these are represented by the cubic polynomial curve. The unit may be successfully operated by adjusting suitably the blade setting angle and the load.

Another trail was done also so that to operate the wind power unit successfully, which is shown in Fig. 3-23, where the operating conditions denoted with the selected front and rear blade setting angles β_F and β_R , and the load. Here, the rotational behavior of the wind power unit is close to desired behavior, but the rated output is too small. The output was kept nearly constant at P=120 W in the wind velocity higher than V=8.6 m/s, and was the maximum at each V in the slower wind velocity. Figure 3-24 also shows the operating conditions denoted with the selected front and rear blade setting angles β_F and β_R , and the load. Here, the rated output of the wind power unit is close to desired output, but the rotational behavior of the tandem wind rotors is not similar to the desired behavior. The rear wind rotor did not work in the blowing mode although through higher wind velocities. The output was kept nearly constant at P=981 W in the wind velocity higher than V=11.4 m/s, and was the maximum at each V in the slower wind velocity

Such operations, however, are not expected and not acceptable for the proposed wind turbine unit because the final target of the serial researches is to get automatically the above operation by the tandem wind rotor works in cooperation with the double armatures of the generator. Consequently, it is necessary to improve more and more the

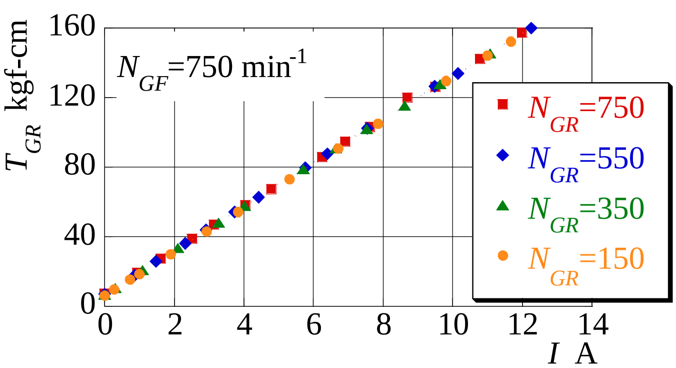


Fig.3-25 Torques and induced currents of inner armature at different rotational speeds

blade profiles to make them suitable for the front and the rear wind rotors.

3.9 Improvement in wind rotor profile:

From the field test on the truck, it was shown that the small sized rear wind rotor which is attached to the inner armature of the generator sometimes hardly counter rotates with the large sized front wind rotor, especially at low wind velocity and high applied load. For this reason, the author designed a new profile for wind rotor blade putting in mind the operating conditions that can be taken from Fig.3-25, where at the very low inner armature rotational speed which is corresponding to N_R=50 min-1, and T_{GR}=7.69 kgf-cm, the wind power unit can have a cut in wind velocity of V=2 m/s. This happens because the profile of the new proposed blade has constant chord length c=150 mm from the hub to the tip, as shown in Fig 3-26 in order to produce the desirable torque, and the attack angle is kept constant (α=18 degrees) from the hub till 3/4 the length of the blade towards the tip, as shown in Fig. 3-27 to get high lifting force at low wind velocity, and to make the rear wind rotor able to counter rotate against the front wind rotor. The rest of the blade length has increasing attack angle so that to gain the fruitful power at higher wind velocities. This will be corresponding to a rated wind

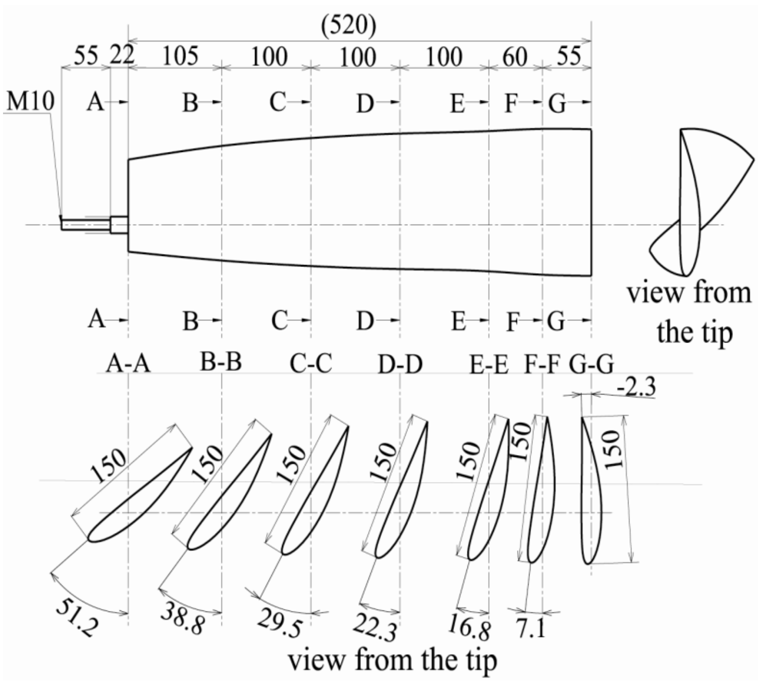


Fig. 3-26 Improved wind rotor profile

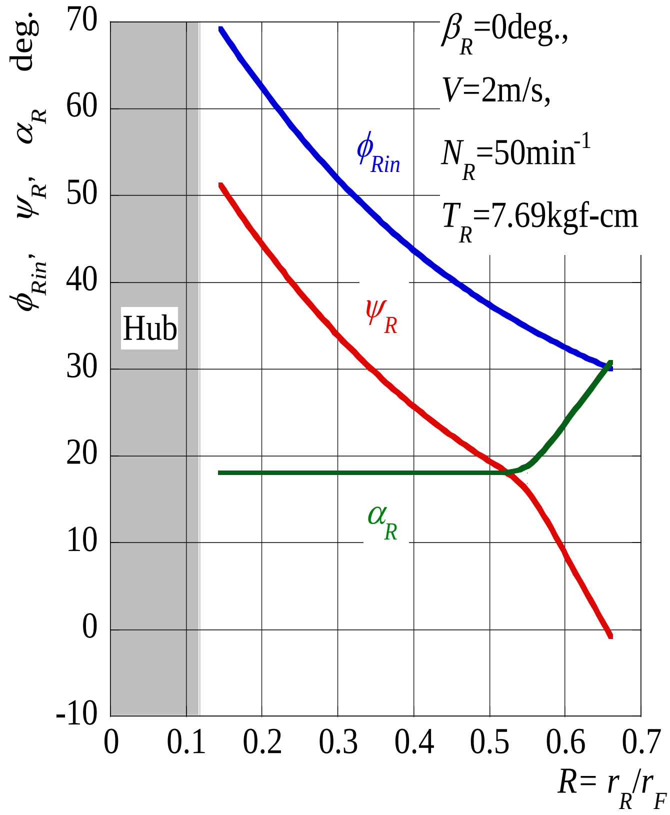


Fig.3-27 Angles of improved blade design

velocity V=8 m/s, N_R=750 min-1, and a torque T_{GR}=157 kgf-cm. The author feels that this new blade design has more promise for higher performance for the unique wind power unit.

Conclusions:

The next step after preparing the unique type wind power generators with double rotational armatures, and designing and manufacturing the tandem wind rotors was to examine the performance of the wind power unit in the field. Experiments first were done using the doubly fed induction generator with double rotational armatures, equipped with the previously designed tandem wind rotors. The field test site was located on a hill close to the seashore of Wakamatsu city in Japan. After studying the wind conditions in the field, and the magnitudes and directions of the wind velocities were analyzed, the following main points were found:

1. The highest wind velocity which was around V=7m/s started from 12 o'clock at night and reached its peak of V=8m/s at four o'clock morning, then started gradually to fall down till it reached V=3.5m/s around 9 o'clock morning, then become steady around this value till the end of the day. This cycle was repeated during January 2007.

2. The wind power unit could not operate properly at low wind velocity less that 4 m/s (cut in wind speed).

Experiments were done by the help of a pick up truck. The new site of the tests was chosen this time just beside the see-shore of Wakamatsu ward, where there are 10 huge wind turbine units working effectively and connected to the electric grid. Two straight roads, each of them is of about 1.5 Km were used in the experiments. One road was located in the north-south direction, while the other one was located at the east-west direction. The wind at both roads was calm and its direction was nearly constant. The main results of the experiments were as following:

3. The performance of the wind power unit is affected markedly by the blade setting angles of both tandem wind rotors. The optimal values for single wind rotor was β_F = 0 at lower applied load, and 20 degrees at higher applied loads. In case of Tandem wind rotors $\beta_F = \beta_R$ =20 degrees gave relatively better response to the wind velocity.

4. The profiles of the tandem wind rotors need to be modified/optimized so that to overcome the static torques of the generator due to electromagnetic and frictional losses.

5. In general, this synchronous type permanent magnet generator together with the designed wind rotors could achieve the required performance in the field by the controlling the load together with the blade setting angles. But this recommend an optimization for the rotor profiles.

Some trails were done in which the wind power unit could operate successfully. This was done by adjusting the blade setting angles β_F, β_R and the bulb load. Such operations, however, were not expected and were not acceptable for the proposed wind turbine unit because the final target of the serial research was to get automatically the above operation by the tandem wind rotor works in cooperation with the double armatures of the generator.

6. A new blade design was introduced that may give higher performance for the unique wind power unit.

Chapter 4

Advanced Technology

The previous field test results on the truck have shown that there is a need for optimizing the profiles and dimensions of the tandem wind rotor blades. The numbers of blades for both tandem wind rotors were optimized before, as was shown in chapter 2. Although counter rotation between tandem wind rotors was experimentally verified in the field, but because the profile of tandem wind rotors were not optimized yet, the rear wind rotor was hardly able to rotate as tandem wind rotor at low wind velocities and high loads.

This chapter shows the experiments which were done to improve the behavior of the wind power unit concentrating on optimizing the dimensions and profile of the tandem wind rotors. Optimal value for diameter ratio between the rear and front wind rotors was proposed. Suitable values for axial distance between tandem wind rotors, blade setting angles, and different blade profiles were presented. In general, the improvement in the rotor profile and dimensions may improve the performance of the wind power unit.

4.1 Tandem Rotors Against Single Wind Rotors:

Figure 4-1 shows the output and the rotational torque coefficients of the wind rotors with the optimal blade numbers Z_F=3 and Z_R=5, where C_M is the rotational torque coefficient [$=T/(\rho AV^2 d_F/4$]. The experimental coefficients at the various wind speeds are represented with one curve against λ_T, that is, the similarity laws were confirmed to the wind speed, for not only the single wind rotor but also the tandem wind rotors. The best relative tip speed ratio giving the maximum output was about three times as fast as that of the single/front wind rotor given by the fine dot line. This was induced mainly from the rear wind rotor speed λ_R. The maximum output was about three times as high as that of the single wind rotor.

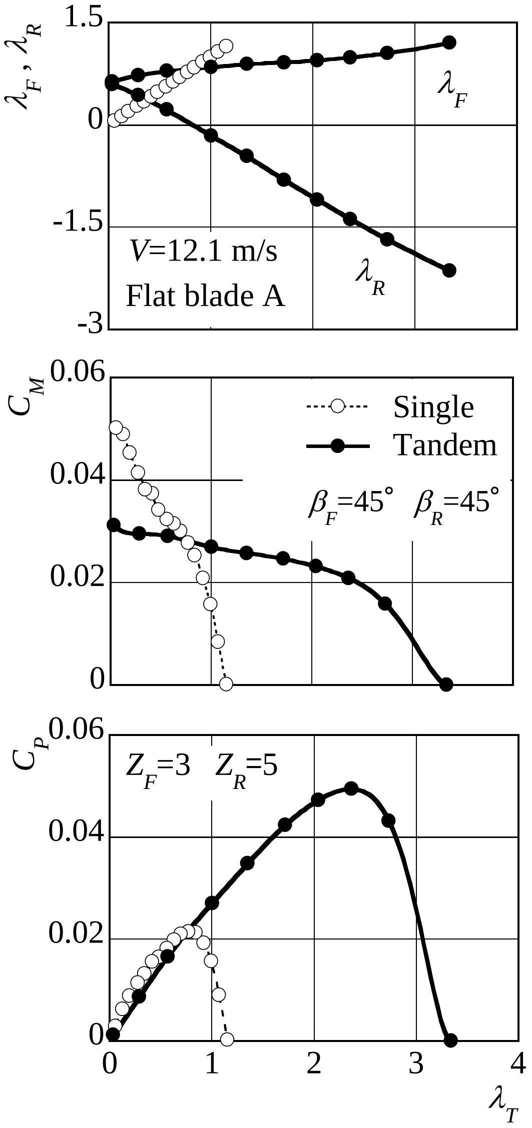


Fig. 4-1 Comparison between single and tandem wind rotor

The optimal tip speed ratio 7-8 of the conventional propeller type wind turbine can not be obtained naturally in the single wind rotor, because the flat blades works at the abnormal attack angle such as the negative angle in the blade tip side and the positive angle in the blade root side.

4.2 Effect of Chord on the Performance

The flow separates from the flat blade surface due to the abnormal attack angle,

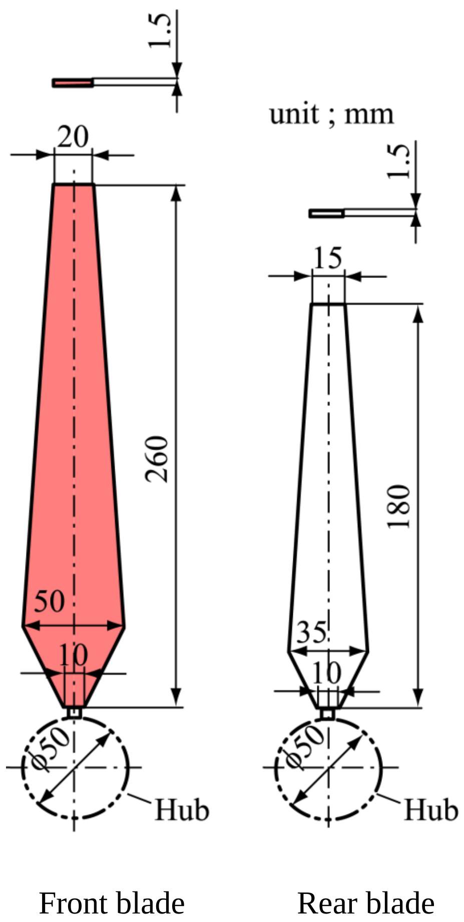


Fig. 4-2 Flat blade B

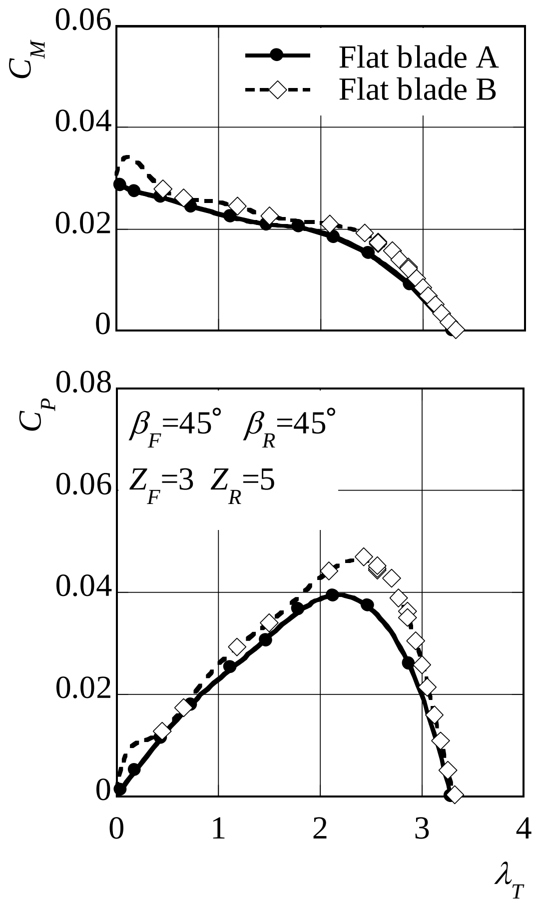
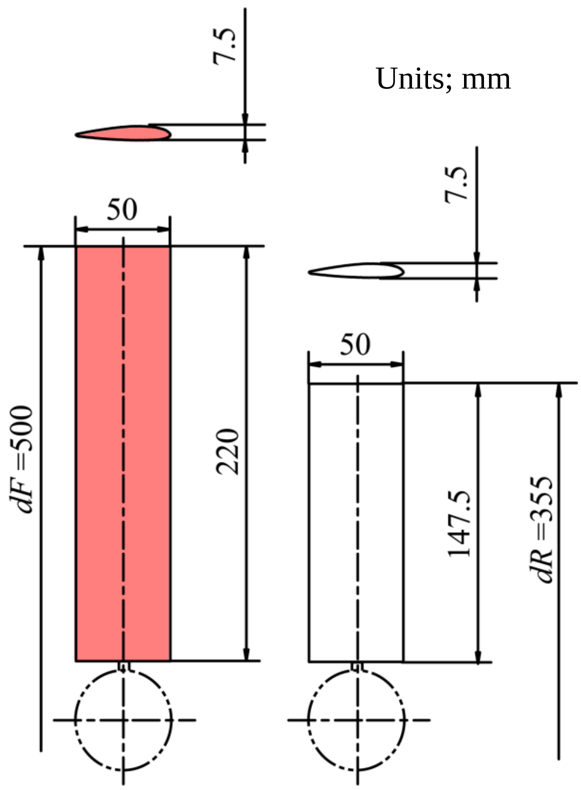
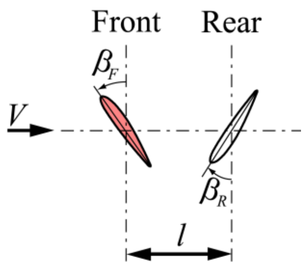


Fig. 4-3 Effect of chord on the performances

and the flow separation affects markedly the wind rotor work. To investigate such effects, another flat blade profile called blade B was used as shown in Fig. 4-2. Chord of the front and the rear blades were changed linearly in the blade height, and the surface areas are almost the same those of the flat blade A previously used in chapter 2. Figure 4-3 shows the output and the rotational torque coefficients, C_P and C_M, in comparison with those of the flat blade A. Both coefficients of the flat blade B are higher than those of the blade A and the relative tip speed ratio λ_T giving the maximum C_P becomes slightly faster. The attack angle of the flat blade changed markedly from the positive at the blade root to the negative at the blade tip. The negative attack angle close to the blade tip causes the flow stall on the pressure surface of the blade, and such a stall deteriorates the rotational speed and torque. The drag force induced from the stall becomes large with the increase of the attack angle and/or the blade chord. That is, the rotor work of the flat blade B with the short chord at the tip are slightly good as



Front blade Rear blade



Blade setting angles

Fig. 4-4 Cambered blade C

compared with the blade A with the long chord, as the rotational torque is determined mainly by the flow condition in the tip side.

4.3 Verification of Superior Operations Using Cambered Blade:

The superior operations of the unique wind power unit were presented at chapter 2 using flat blade A. Another blade profile called Blade C shown in Fig. 4-4 which has a moderate camber, and its profile is two dimensional without the twist was used to verify the superior operations and study the effect of the chamber on the performance. Experimental rigs and procedure used are the same as the previous ones done on the flat blade A, while the front wind rotor has the nose cone. Figure 4-5 shows the performances of the model rotors, where the rated wind speed was set at V=11 m/s, while front and rear optimized blade numbers are Z_F=3 and Z_R=5 same as flat blade A as previously mentioned in chapter 2. Front and the rear blade setting angles are

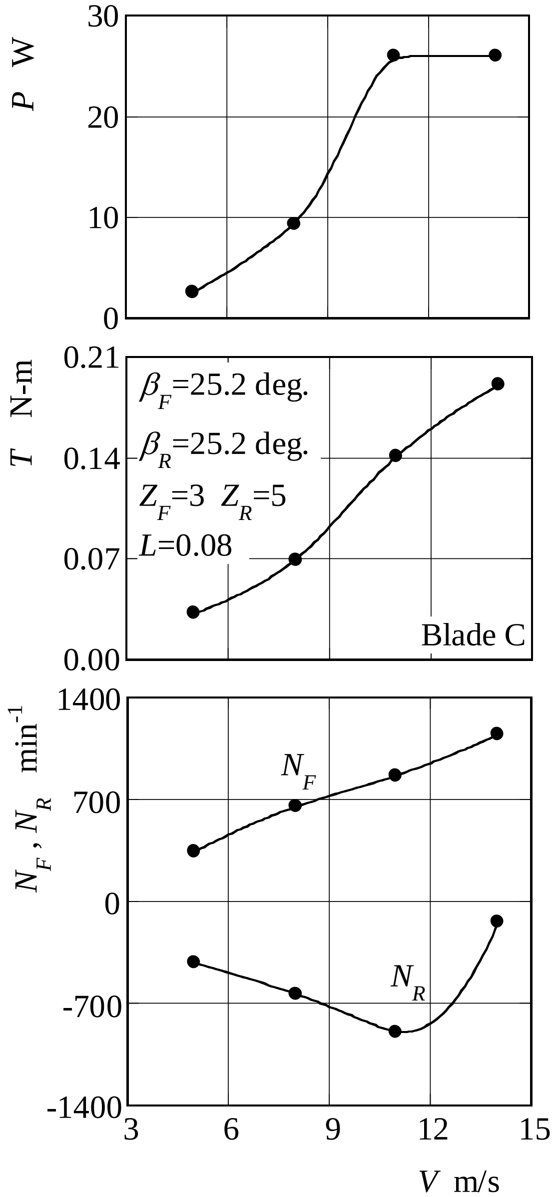


Fig.4-5 Wind turbine performances

$\beta_F = \beta_R$=25.2 degrees, and the axial distance between both wind rotors is L=0.08 (=l/d_F, l: axial distance given in Fig. 4-4, d_F: diameter of the front rotor). It is confirmed, as predicted before, that the rotational speeds of the front and the rear wind rotors N_F and N_R, are adjusted successfully and automatically and the output is kept constant in the rated operating mode without using break/pitch control mechanisms. Besides, the abnormally high rotation of the large sized front wind rotor N_F is suppressed well by the rotation of the rear wind rotor N_R in the blowing mode at the faster wind velocities.

4.4 Effect of Blade Camber and Thickness

The work of the rotor could be improved more when the two-dimensional cambered blade C was used, in comparison with flat blade A. Figure 4-6 shows the coefficients C_P and C_M of the cambered blade C. It is noticed significantly that the work of the cambered blades is obviously better and the relative tip speed ratio giving the maximum C_P become higher.

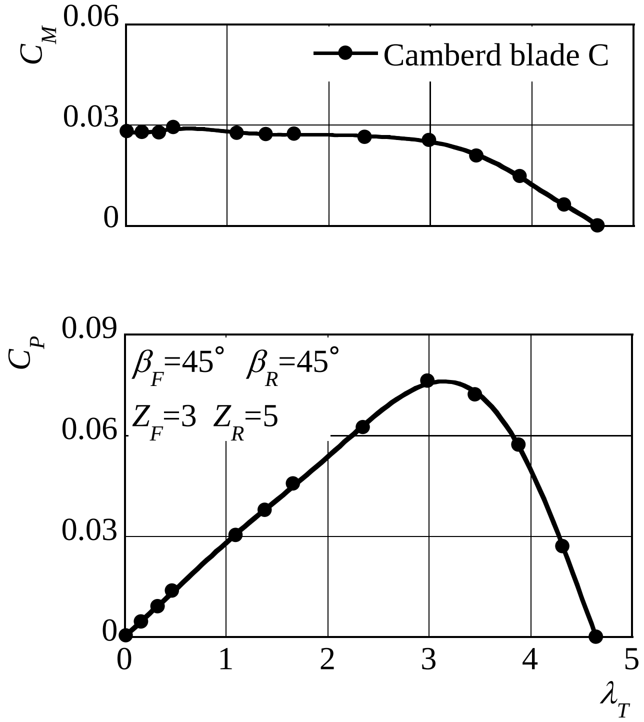
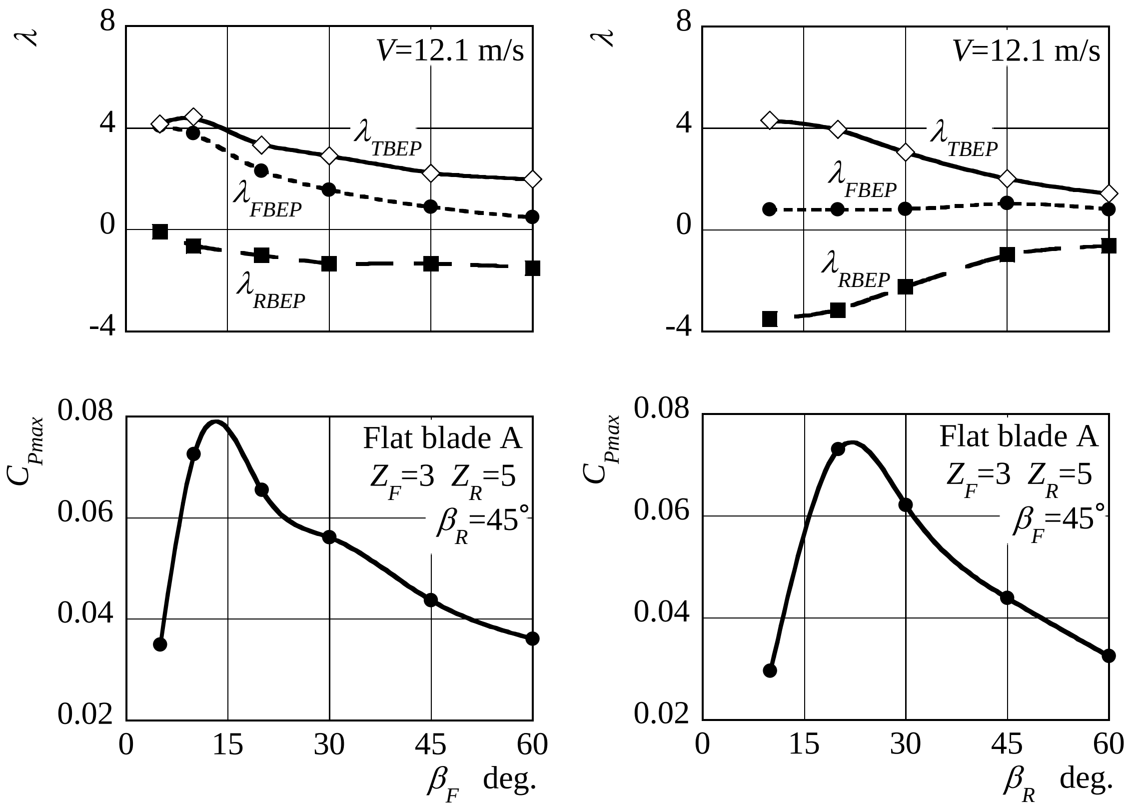


Fig. 4-6 Effect of camber and thickness on the characteristics

4.5 Effect of Blade Setting Angles

There is a direct effect of blade setting angles on the output coefficient C_P. The effect of blade setting angles on the maximum output coefficient C_{Pmax} and the tip speed ratios giving C_{Pmax} (λ_{TBEP}, λ_{FBEP}, λ_{RBEP}: the relative, the front and the rear tip speed ratios at best efficiency point) of the flat blade A are shown in Fig. 4-7, when the front blade angle β_F is changed in keeping the rear blade angle β_R=45 degrees or β_R is changed in keeping β_F=45 degrees. The optimal angle of the front blade was nearly close to β_F=13 degrees at β_R=45 degrees and the angle of the rear blade is nearly close to β_R=22 degrees at β_F=45 degrees. It is shown that the relative tip speed ratio λ_T is faster due to λ_F as for the optimal setting angle of the front blade as shown in Fig. 4-7(a), and λ_{TBEP} is faster due to λ_R as for the optimal setting angle of the rear blade as shown in Fig. 4-7(b). Such results mean that the attack angles must be optimized as the tandem



a) Effect of front blade angle a) Effect of rear blade angle

Fig. 4-7 Effect of blade setting angle on maximum output wind rotors, taking account of the flow interactions between both wind rotors.

This experiment was done again using another new blade profile called Blade E, which has no camber, and is two dimensional, as shown in Fig. 4-8, so that to make the blade chord length closes to the profile of the prototype. Figure 4-9 shows the output coefficient C_P and the rotational torque coefficient C_M against the relative tip speed ratio λ_T at the front blade setting angle β_F=11.3 degrees. The output and the rotational torque are affected markedly by the rear blade setting angles β_F. The flow discharged from the front wind rotor has large swirling velocity component, because the rotational torque of the front wind rotor corresponds to the angular momentum change of the flow thorough the wind rotor. That is, it is very important to optimize the setting angle, namely the attack angle, of the rear blade. Figure 4-10 shows the optimal relative tip speed ratio λ_{Topt} giving the maximum output C_{Pmax} while keeping the front blade setting angle

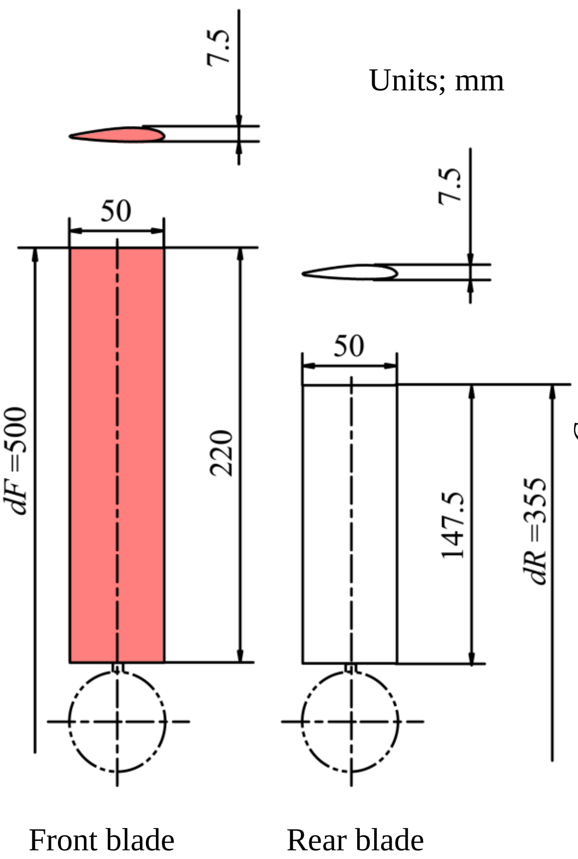


Fig. 4-8 Blade E

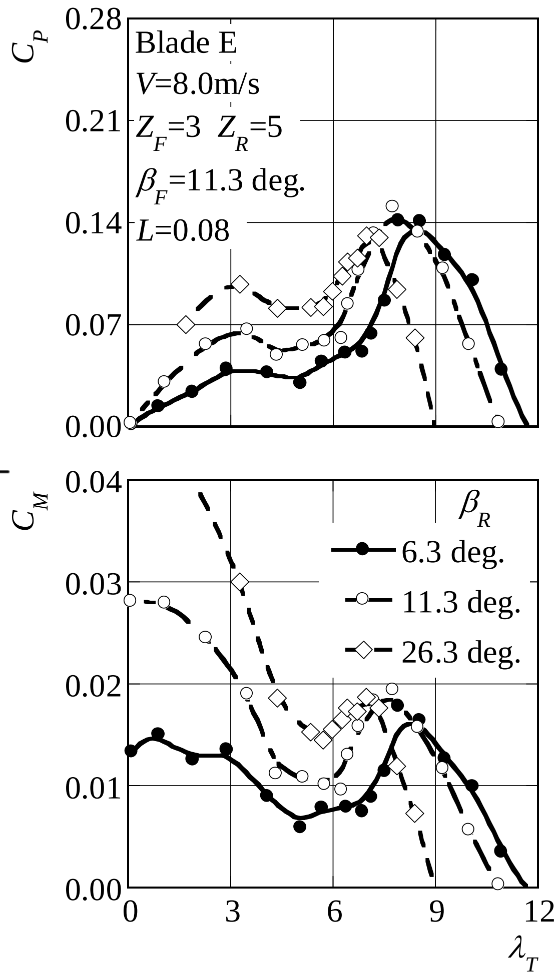


Fig.4.9 Performances of Blade E

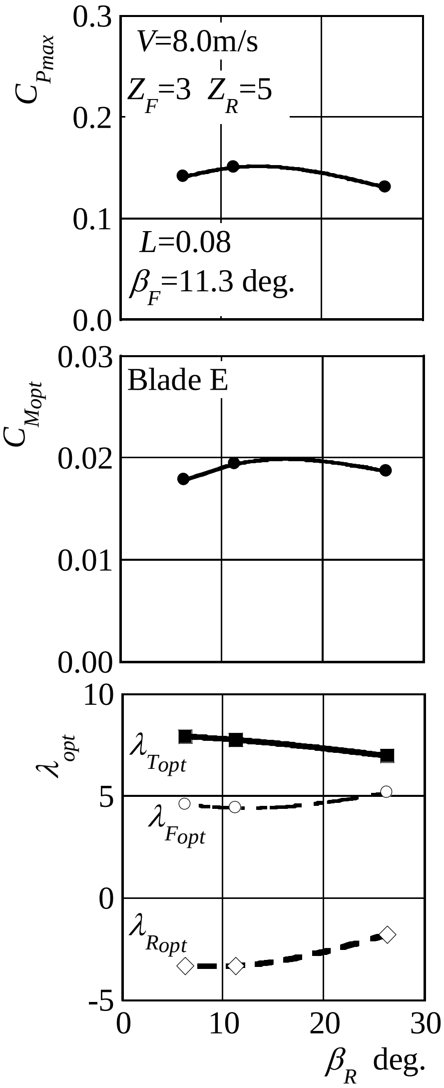


Fig. 4.10 Effect of rear blade setting angle

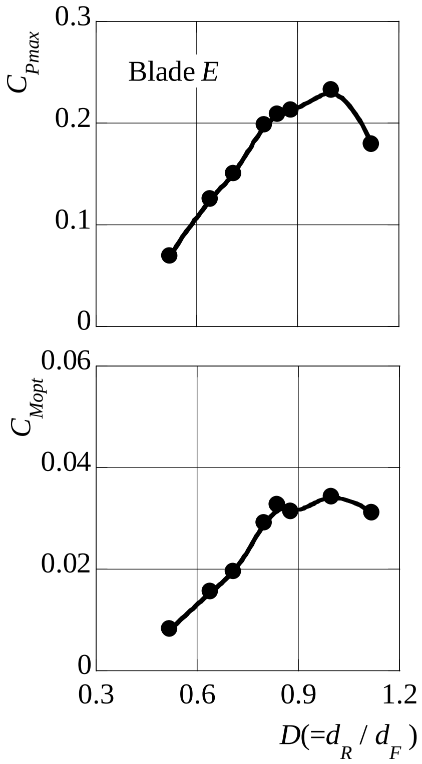


Fig.4-11 Effect of blade diameter ratio

constant, β_F=11.3 degrees, where λ_{Fopt} and λ_{Ropt} are the tip speed ratio of the front and the rear wind rotors. The highest value of the output coefficient is given at nearly β_R=13degrees as for Blade E. It is necessary, however, to optimize the setting angle at each radial position, because the swirling velocity component at the inlet of the rear wind rotor changes markedly in the radial direction.

4.6 Suitable Diameter Ratio

These blade setting angles were used to investigate the effect of the rotor diameter

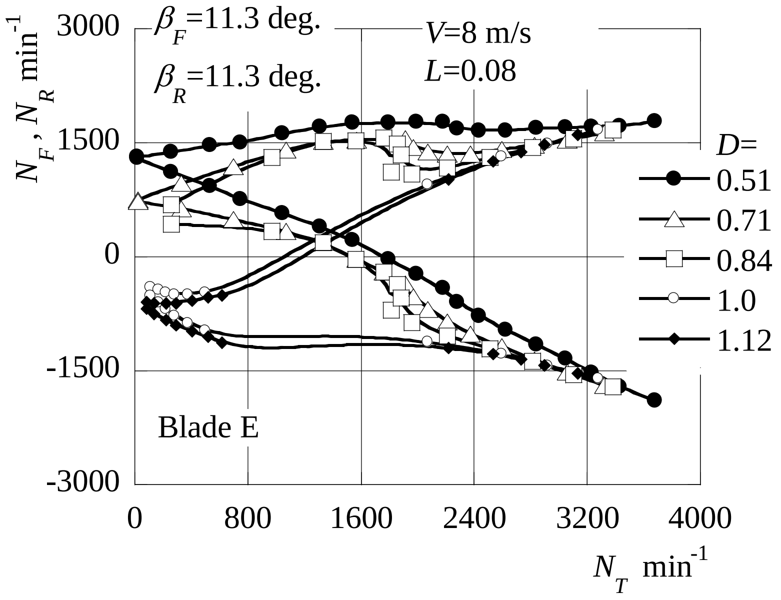


Fig. 4.12 Effect of blade diameter ratio on the rotational speeds

ratio *D* [=(rear diameter)/(front diameter)] on the performance. Figure 4-11 shows that the output coefficient C_{Pmax} and C_{Mopt} increase with the increase of *D*, until these reach the maximum values at *D*=1. Such tendencies are similar to those obtained from the blade E.

Figure 4-12 show the front and the rear rotational speed N_F and N_R against the relative rotational speed N_T, where the rotational direction of the front rotor is positive. It is important to pay attention to the behavior of the rear wind rotor. That is, the rear wind rotor must run not only in the opposite direction (counter-rotation) against the front wind rotor when the relative rotational speed N_T is faster, but also in the same direction when the relative rotational speed is slower. That is, the diameter ratio *D*=1 is not acceptable because the front wind rotor runs in the same direction of the rear wind rotor when the relative rotational speed is slow. Resultantly, the diameter ratio *D*=1 does not fulfill the idea of the intelligent wind turbine generator mentioned above. Therefore, the optimal diameter ratio having the sufficient output is at *D*=0.84. This values was the diameter ratio between the rear wind rotor and the front wind rotor just before *D*=1. The experiments were done on other different blade profiles, and the same result was found at each different profile used.

4.7 Suitable Axial Distance

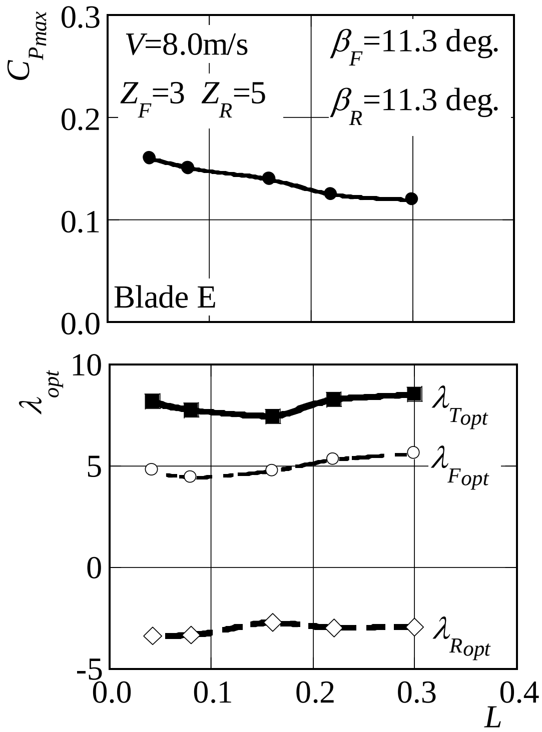


Fig.4.13 Effect of the axial distance

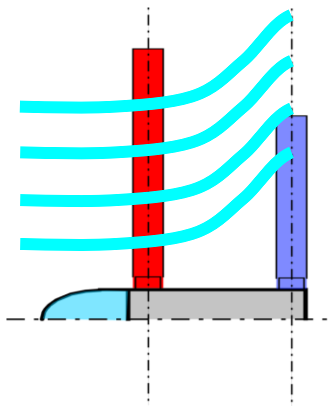


Fig. 4-14 Wind flow between tandem wind rotors

At the optimal profiles where D=0.84, β_F=11.3, and β_R=11.3 degrees, the effect of the axial distance L between both wind rotors on the performance was examined as shown in Fig. 4-13. Output was higher at the smaller distance between both wind rotors, because when the distance between the tandem wind rotors is long, the flow will be biased to outside as shown in Fig. 4-14. Data suggest that the best location of the rear wind rotor is to be set as close as possible to the front wind rotor, taking the bend of the blade into account.

Conclusions

Although a counter rotation between tandem wind rotors was experimentally verified in the field, the profile of tandem wind rotors were not optimized. However, the rear wind rotor was hardly able to rotate as tandem wind rotor in low wind velocities and high loads. Experiments that were done to improve the behavior of the wind power unit concentrating on optimizing the dimensions and profile of the tandem wind rotors. The main results can be summarized in points as follows:

1. The superior operation of the peculiar generator was verified using different blade profiles. The abnormally high rotation of the front wind rotor N_F, which can not be avoided by the conventional single wind rotor without the breaking and/or pitch control mechanism, is also suppressed well by the rotation of the rear wind rotor N_R in the blowing mode at the faster wind speed.

2. When the chord of the blade was changed so that the blade is linearly tapered from the hub to the tip, the output coefficient was increased by 18%.

3. When using cambered blades instead of flat blades, the maximum output coefficient of the cambered blade was increased nearly 1.6 times more than that for the flat blade, while the relative tip speed ratio was increased also by nearly 1.4 times.

4. Blade setting angles have direct effect on the behavior of the wind rotor. Every different blade profile has its own optimal blade setting angles that gives relatively better performance. For flat blade A, the optimal angle of the front blade was nearly close to β_F=13 degrees at rear blade setting angle β_R=45 degrees and the angle of the rear blade was nearly close to β_R=22 degrees at β_F=45 degrees. For blade E, the highest value of the output coefficient was given at nearly β_R=13degrees.

5. Diameter ratio "*D*" between the small sized rear wind rotor and the large sized front wind rotor has great effect of the output. The maximum output and torque coefficients increase with the increase of *D*, until these reach the maximum values at *D*=1, but this value does not fulfill the idea of the intelligent wind turbine generator mentioned above. Therefore, the optimal diameter ratio having the sufficient output was found at *D*=0.84.

6. Effect of the axial distance *L* between both wind rotors on the performance was examined, and data suggested that the best location of the rear wind rotor is to be set as close as possible to the front wind rotor, because the output is higher at the smaller distance between both wind rotors. The reason is that when the distance between the tandem wind rotors is long, the flow will be biased to outside and fewer wind will reach the rear wind rotor.

Chapter 5

Conclusions

Wind power is a significant promising source of renewable energy that will play a very important role in the 21st century. Wind turbines are very effective to generate the electrical energy from wind power. There is a great need/obligation to exploit the renewable energy because of the rapid decrease of the earth's fossil energy sources, and the global warming resulting from utilizing them. Propeller type wind turbines are very effective to generate the electric power; however, these conventional turbines had some weak points that can be summarized as follows:

- The size of the wind rotor must be correctly/appropriately selected in conformity with the wind circumstances. Although large-sized wind rotors generate high output at strong wind, but they do not operate properly at weak wind. On the contrary, small-sized wind rotors are suitable for weak wind, but their power generation is low. This problem could be solved using the proposed wind power unit. The counter-rotation under the rated wind speed makes output higher in poor wind circumstances, while at high wind velocity, it generates higher output than the single wind rotors.

- It is necessary to be equipped with the brake and/or the pitch control mechanisms, to suppress the abnormal rotation and the generated overload at the stronger wind. This point is also solved in the unique wind power unit because at higher wind velocities, the rear wind rotor rotates in the same direction of the front rotor (blowing mode) forcing the abnormal rotational speed of the front wind rotor to slow down without using brake and/or the pitch control mechanisms.

- Fluctuation of wind rotor speed may lead to poor quality of the electrical power. In the proposed unit, the relative rotational speed between tandem wind rotors which corresponds to the electrical output frequency is adjusted automatically pretty well with response to the wind velocity keeping good quality of the electric power.

This work proposes/presents a new unique type horizontal wind power unit composed of the large-sized front wind rotor, the small-sized rear wind rotor and the peculiar generator with the inner and the outer rotational armatures. The front and the rear wind rotors drive the inner and the outer armatures. This unit is unique, as during the experiments on the small scale rotors, the rotational speeds of the tandem wind rotors are adjusted pretty well in cooperation with the two armatures of the generator in response to the wind speed. The rotational torque is counter-balanced between the inner and the outer armatures in the generator. As for the wind rotors, the rotational torque of the front wind rotor must equal that of the rear wind rotor, but in the opposite direction, while the rotational directions of both rotors/armatures are free. The rotational direction and speed of the rotor/armature are automatically determined in response to the wind circumstance. The output must be kept constant and this can be done if the rotors are designed so as to keep the relative rotational speed multiplied by the rotational torque equal a constant. The operation of the unique generator with double rotational armatures is verified in the field.

Experiments were done to verify the superior operations of the unique wind power unit. Bench tests were done on both unique wind turbine generators, namely the doubly fed induction generator with double rotational armatures, and the permanent magnet synchronous generator with double rotational armatures. Front and rear wind rotors were designed. Concerning the experiments that were done on the doubly fed induction generator with double rotational armatures, the main results are as following:

1. In order to keep the output frequency constant at f_1=60 Hz, , its found that the input frequency f_2 is inversely proportional with the relative rotational speed between tandem wind rotors N_T.
2. To keep the output voltage constant at E_1=200V, the input voltage E_2 will not depend only on N_T but also on P_1, namely the load
3. The input P_2 comes to be negative at the higher rotational speed than the synchronous speed N_T=900 min, which means adding the power to the output.
4. When keeping the output voltage at 200V, and the output frequency constant at 60 Hz, it was shown that the output increases with the increase of the induced voltage E at the same I, while E is proportional to the relative rotational speed N_T and I

determine the rotational torque.

Preparations were done to start the field tests on the wind power unit consisting of the permanent magnet synchronous generator with double rotational armatures, equipped with the tandem wind rotor mentioned before. This synchronous generator was used successfully in hydroelectric turbines. The main results are as following

5. It was verified experimentally that the torques of the inner and the outer armatures are equal and counter balance (T_{GR}=T_{GF}).

Concerning the design of the tandem wind rotors, the following points were noticed:

6. The optimum number of blades for the front wind rotor is three, while for the rear wind rotor is five.
7. Tandem wind rotors of MEL012 profile were designed and manufactured using basic aerodynamic theories, mainly Blade Element Momentum model.
8. The diameter of the large sized front wind rotor was 2m , while the diameter of the small sized rear wind rotor was 1.33m.

The next step after preparing the unique type wind power generators with double rotational armatures, and designing and manufacturing the tandem wind rotors was to examine the performance of the wind power unit in the field. Experiments first were done using the doubly fed induction generator with double rotational armatures, equipped with the previously designed tandem wind rotors. The field test site was located on a hill close to the seashore of Wakamatsu city in Japan. After studying the wind conditions in the field, and the magnitudes and directions of the wind velocities were analyzed, the following main points were found:

9. The highest wind velocity which was around V=7m/s started from 12 o'clock at night and reached its peak of V=8m/s at four o'clock morning, then started gradually to fall down till it reached V=3.5m/s around 9 o'clock morning, then become steady around this value till the end of the day. This cycle was repeated during January 2007.

10. The wind power unit could not operate properly at low wind velocity less that 4 m/s

(cut in wind speed).

Experiments were done by the help of pick up truck. The new site of the tests was chosen this time just beside the see-shore of Wakamatsu ward, where there are 10 huge wind turbine units working effectively and connected to the electric grid. Two straight roads, each of them is of about 1.5 Km were used in the experiments. One road was located in the north-south direction, while the other one was located at the east-west direction. The wind at both roads was calm and its direction was nearly constant. The main results of the experiments were as following:

11. The performance of the wind power unit is affected markedly by the blade setting angles of both tandem wind rotors. The optimal values for single wind rotor was $\beta_F = 0$ at lower applied load, and 20 degrees at higher applied loads. In case of Tandem wind rotors $\beta_F = \beta_R = 20$ degrees gave relatively better response to the wind velocity.

12. The profiles of the tandem wind rotors need to be modified/optimized so that to overcome the static torques of the generator due to electromagnetic and frictional losses.

13. In general, this synchronous type permanent magnet generator together with the designed wind rotors could achieve the required performance in the field by the controlling the load together with the blade setting angles. But this recommend an optimization for the rotor profiles.

14. Some trials of reasonable operations were done and could operate the wind power unit successfully. This was done by adjusting the blade setting angles β_F, β_R and the bulb load. Such operations, however, were not expected and were not acceptable for the proposed wind turbine unit because the final target of the serial researches was to get automatically the above operation by the tandem wind rotor works in cooperation with the double armatures of the generator.

15. A new blade design was introduced that may give higher performance for the unique wind power unit.

Although counter rotation between tandem wind rotors was experimentally verified in the field, but because the profile of tandem wind rotors were not optimized yet, the rear wind rotor was hardly able to rotate as tandem wind rotor at low wind velocities and high loads. Experiments that were done to improve the behavior of the wind power unit concentrating on optimizing the dimensions and profile of the tandem wind rotors. The main results can be summarized in points as follows:

16. The superior operation of the peculiar generator was verified using different blade profiles. The abnormally high rotation of the front wind rotor N_F, which can not be avoided by the conventional single wind rotor without the breaking and/or pitch control mechanism, is also suppressed well by the rotation of the rear wind rotor N_R in the blowing mode at the faster wind speed.

17. When the chord of the blade was changed so that the blade is linearly tapered from the hub to the tip, the output coefficient was increased by 18%.

18. When using cambered blades instead of flat blades, the maximum output coefficient of the cambered blade was increased nearly 1.6 times more than that for the flat blade, while the relative tip speed ratio was increased also by nearly 1.4 times.

19. Blade setting angles have direct effect on the behavior of the wind rotor. Every different blade profile has its own optimal blade setting angles that gives relatively better performance. For flat blade A, the optimal angle of the front blade was nearly close to β_F=13 degrees at rear blade setting angle β_R=45 degrees and the angle of the rear blade was nearly close to β_R=22 degrees at β_F=45 degrees. For blade E, the highest value of the output coefficient was given at nearly β_R=13degrees.

20. Diameter ratio "*D*" between the small sized rear wind rotor and the large sized front wind rotor has great effect of the output. The maximum output and torque coefficients increase with the increase of *D*, until these reach the maximum values at *D*=1, but this value does not fulfill the idea of the intelligent wind turbine generator mentioned above. Therefore, the optimal diameter ratio having the sufficient output was found at *D*=0.84.

21. Effect of the axial distance *L* between both wind rotors on the performance was examined, and data suggested that the best location of the rear wind rotor is to be set as close as possible to the front wind rotor, because the output is higher at the smaller distance between both wind rotors. The reason is that when the distance between the tandem wind rotors is long, the flow will be biased to outside and fewer wind will reach the rear wind rotor.

Future Research Avenues

In the near future, my concentration will be on optimizing the profile of both tandem wind rotors, studying deeply the flow interaction between the front and the rear wind rotors, and analyzing mathematically and experimentally more and more the performance of each component of the wind power unit, so that to achieve the best performance. My dream is to see this unique wind power produced commercially, in large scales, and that its superior operations can solve all of the problems of conventional wind power units, so that the societies can have a more secure and stable source of energy.

Acknowledgements

First and most of all, I am very grateful to my Creator the Almighty **ALLAH**, the most Merciful and beneficent, for giving me the strength and patience throughout my study at Kyushu Institute of Technology and all periods of my life.

I would like to express my thanks to the **Egyptian Ministry of Higher Education** for giving me this opportunity to study Ph.D. at Japan, and its total support through the Egyptian Government Grant. My deepest thanks for its continuous help, and support throughout four period of my study in Japan.

My deep thanks come to **Professor Toshiaki Kanemoto**, my Ph.D. supervisor, for his guidance, his kind support, continuous encouragement and help throughout the accomplishment of these studies. I appreciate his in-exhaustive efforts, unending cooperation and advice, his deep insights that always found solutions when problems supervened and very creative criticism. I will never forget his kindness and patience in dealing with my style and character, which are very different from that of Japanese. I also wish to thank **Professor Yoshinobu Kubo**, **Professor Hiroshi Tsukamoto**, **Professor Takaharu Tsuruta**, and **Professor Yuji Hattori** for accepting to be staff members of the dissertation committee of this thesis and also for the time they spent in reading and verifying this thesis. Special gratitude for Mr. **Robert Long**, the American Professor who teaches English in KIT for accepting reviewing my thesis.

My thanks and appreciation to all my colleagues and friends at the Department of Mechanical Engineering, Kyushu Institute of Technology, especially **Mr. Inada, Mrs. Konno, Mr. Ikeda, Mr. Mitarai,** and **Mr. Kubo** for their educational utilities, help and friendship.

I wish to express my deep appreciation to all Professors at Production and Mechanical Design Department, Mansoura University, Egypt, especially **Prof. Dr. Ibrahim Eleewa**, and **Prof. Dr. Mohamed Fanni**, who were my Master Supervisors, and special gratitude to **Prof. Dr. Alameer Sami,** whose advice and support were beyond acknowledgement. Special thanks to **Eng. Abdel-Hameed Shoman** for offering all facilities of his factories (Shoman Factories) during my Master study.

Also, it is a great opportunity to express my sincere appreciation and my deep respect **to all staff members** of Department of Production and Mechanical design, Mansoura

University, Egypt, for their kind help and encouragement.

I am also grateful to my family; my beloved wife Dr. **Abeer Ramadan**, and my beloved sons **Usama**, **Yusef**, and **Yaser**. I would not be able to complete this work without their unwavering love, patience, prayer, and supplication (Doa'a). My deep thanks to all of them for their patience and understanding during the many hours of working and preparing this study and for the many years of living as foreigners outside our home country Egypt.

I would like to make a deep thank my parents (my beloved Father **Mohamed Galal** who already passed away and I ask ALLAH to bless him in his grave and put all my good deed in his account and enter him Aljanaah, my beloved Mother **Fatma Abdel Galeel** for her support and doa'a, and my father in law Eng. **Ramadan Alfarahaty**, my mother in law Mrs. **Nadya Abu-ssafa** for their doa'a, my brothers Eng. **Tarek, and Eng. Wael, and sisters Howaida, Halal, and Heba,** their husbands and children, and my brothers in law Captain Ahmed , and Captain Mohamed. Also, all my Muslim friends in Japan and specially in **MAKITA (Muslim Association in KITAkyushu)** for their concern and encouragement.

I would like to thank all my brothers in Islam in my country and my home town Mansoura city for their help, brotherhood and doa'a to me. I am thankful to all who knows me from near or far and wished me success. Finally, I would like to thank the staff of our Embassy in Japan for their encouragement and support during my stay in Japan.

References

1- http://www.superstock.com/stock-photos-images/1555R-147089

2- http://www.drillingconsultants.net/

3- http://www.etftrends.com/2008/09/nuclear-companies-deal-could-be-power-boost-etfs.html

4- http://solarkismet.wordpress.com/2006/01/10/coal-legacy/

5- Z. S. Lin, S. G. Wang, “EMD analysis of solar insolation”, *Meteorology and Atmospheric Physics*, 2000, pp123–128, Vol. 93.

6- http://en.wikipedia.org/wiki/Greenhouse_effect

7- Houghton, John, “Global Warming: the Complete Briefing”, *Cambridge University Press*, 1997, pp251.

8- DOE/EIA, “Renewable Energy Trends in Consumption and Electricity”, *Energy Information Administration*, 2008.

9- Asia Pacific Energy Research Centre, “New and Renewable Energy in the APEC Region”, *Prospects for Electricity Generation*, 2004.

10- http://oilblog.pbwiki.com/SA2-4

11- http://www.solarpowersolutionsllc.com/

12- http://www-esd.lbl.gov/ER/geothermal.html

13- http://www.bravenewleaf.com/environment/2008/03/wave-power-gain.html

14- http://www.da-wai.com/photo_detail.asp?PhotoID=60

15- I. Ushiyama, “Renewable Energy Strategy in Japan”, *Renewable Energy*, 1999, Vol. 16, pp1174-l 179.

16- J. Twidell, “Renewable Energy: Implementation and Benefits,” Advances in Power System Control, Operation and Management, 1993, pp. 418-424, vol.1.

17- Müller, Reto; Steinfeld, A., "Band-approximated radiative heat transfer analysis of a solar chemical reactor for the thermal dissociation of zinc oxide", 2007.

18- Tritt, T.; Böttner, H.; Chen, L., "Thermoelectrics: Direct Solar Thermal Energy Conversion", 2008.

19- Holthuijsen, Leo H., “Waves in oceanic and coastal waters”, *Cambridge University Press*, 2007.

20- Secondary Energy Infobook, “Hydropower”, *The Need Project*, 2008, pp. 24-27.

21- http://www.space.com/imageoftheday/image_of_day_040730.html

22- http://www.eoearth.org/article/Tropical_weather_and_hurricanes

23- IEA Wind Energy, *Annual Report*, 2008, pp. 163-170.

24- Ushiyama I., "Small Wind Turbines in Sustainable Urban Environment", *Urban Planning - Sustainable Cities in the framework of the German in Japan*, 2005.

25- Lahmeyer International GmbH, "Zafarana KfW IV Wind Farm", Project Design Document (CDM PDD), 2008, Ver. 03.1, pp. 1-57.

26- Erich Hau. "Wind turbines*", Spring-Verlag Berlin Heidelberg*, 2002, pp. 24.

27- J.F Manwell, J.G McGowan, A.L Rogers, "Wind Energy Explained", *John Wiley and Sons*, 2002.

28- T. Ackermann (ed.), "Wind Power in Power systems", *John Wiley & Sons Inc*, 2005.

29- J.F Manwell, J.G McGowan, A.L Rogers, "Wind Energy Explained", *John Wiley and Sons*, 2002.

30- http://www.flickr.com/photos/21120512.

31- http://www.reuk.co.uk/Darrieus-Wind-Turbines.htm.

32- Sathyajith Mathew, "Wind Energy Fundamentals, Resource Analysis and Economics", *Springer*, 2006, pp. 18.

33- http://www.glengro.com/wind_energy/Ecology.html

34- http://w1.siemens.com/press/en/pp_cc/2007/06_jun/sosep200718_08_(energy-mediasummit2007)_1453274.htm

35- http://www.finfacts.com/irelandbusinessnews/publish/article_1012056.shtml

36- Spera DA, "Wind Turbine Technology", *ASME Press*, 1994.

37- Ackermann T. and L. Soder. "An overview of wind energy-status". Renewable and *Sustainable Energy Reviews*, 2002, pp. 67-127.

38- L. H. Hansen, L. Helle, F. Blaabjerg, E. Ritchie, S. Munk-Nielsen, H. Bindner, P. S_rensen, and Bak-Jensen B. Conceptual survey of generators and power electronics for wind turbines. Technical Report Ris_-R-1205(EN), Ris_ National Laboratory, Roskilde, Denmark, December 2001.

39- Morel L., Godfroid H., Mirzaian A., and Kauffmann J. M. "Double-fed induction machine: converter optimization and field oriented control without position sensor", *IEE Proceedings Electric Power Applications*, 1998, pp. 360-368.

40- Xu L., and Wei C., "Torque and reactive power control of a doubly fed induction machine by position sensorless scheme", *IEEE Transactions on Industry Applications*, 1995, pp. 636-642, vol. 31.

41- Mutschler P., and Hoffmann R., "Comparison of wind turbines regarding their energy generation, "*IEEE 33rd Annual Power Electronics Specialists Conference (PESC)*", 2002, pp. 6-11.

42- Ioannides M. G., and Tegopoulos J. A., "Optimal efficiency slip-power recovery drive", *IEEE Transactions on Energy Conversion*, 1988, pp. 342-348, vol. 3.

43- Datta R., and Ranganathan V. T., "Variable-speed wind power generation using doubly fed wound rotor induction machine-a comparison with alternative schemes", *IEEE Transactions on Energy Conversion*, 2002, pp. 414-421, vol. 17.

44- .Wang S., and Ding Y., "Stability analysis of field oriented doubly-fed induction machine drive based on computer simulation", *Electric Machines and Power Systems*, 1993, pp. 11-24, vol. 24.

45- Heller M., and Schumacher W., "Stability analysis of doubly-fed induction machines in stator flux reference frame", *Proceedings of 7th European Conference on Power Electronics and Applications*, 1997, pp. 707-710, vol.2

46- Bansal RC, Bhatti TS, Kothari DP, "On Some of the Design Aspects of Wind Energy Conversion Systems", *Energy Conversion and Management,* 2002, Vol. 43, pp. 2175–2187.

47- Varol A, Iÿlk.l.c¸ C, Varol Y. "Increasing the Eficiency of Wind Turbines", *Journal of Wind Engineering and Industrial Aerodynamics,* 2001, Vol. 89, pp. 809–815.

48- Rodriguez JM, Fernandez JL, Beato D, Iturbe R, Usaola J, Ledesma P, et al. "Incidence on Power System Dynamics of High Penetration of Fixed Speed and Doubly Fed Wind Energy Systems: Study of the Spanish Case", *IEEE Transactions on Power Systems*, 2002, 17(4), pp. 1089–1095.

49- Rajesh K. Reliability, "Cost Implications of PV and Wind Energy Utilization in Small Isolated System", *IEEE Transactions on Energy Conversion,* 2001, 16(4), pp. 368–373.

50- Pamakumar RA, Abouzahr I, Krishnan k, Ashenayi K., "Design Scenarios for

Integrated Renewable Energy Systems”, *IEEE Transactions on Energy Conversion*, 1995, 40(4), pp. 736–746.

51- J.M. Mej.´a et al,” Simulation of Wind Energy Output at Guajira, Colombia”, *Renewable Energy*, 2005.

52- W Z Shen, V A K Zakkam, J N Sørensen and K Appa, “Analysis of Counter-Rotating Wind Turbines“, 2007.

53- M.B.Sharifian, “Maximum Power Control of Grid Connected Variable Speed Wind System through Back to Back Converters”, *Journal of applied Science*, 2008, pp. 4416-4421.

54- Appa K, “Counter rotating wind turbine system“, *Energy Innovations Small Grant (EISG)- Program Technical Report*, 2002 California, US.

55- Jung S N, No T S and Ryu K W, Renewable Energy, 2005, Vol. 30, pp. 631.

56- Ushiyama, I., Shimota, T. and Miura, Y., “An Experimental Study of the Two Staged Wind Turbines”, *Proceedings of World Renewable Energy Conference*, 1996, pp. 909-912.

57- Navy Electricity and Electronics Training Series, “Introduction to Generators and Motors”, *Professional development and technology center*, 1998.

58- MYERS, L. and BAHAJ, A.S., “Power Output Performance Characteristics of a Horizontal Axis Marine Current Turbine”, *Renewable Energy*, 2006, pp. 197-208.

59- HANSEN, M.O.L., “Aerodynamics of Wind Turbines: Rotors, Loads and Structure”. *James & James (Science Publishers) Ltd*., 2001, pp. 152.

60- BURTON, T., et al., “Wind Energy Handbook”, *John Wiley and Sons Ltd*., 2001, pp. 624.

61- Ushiyama, I., “An Introduction to Wind Turbine Technology”, 2002, pp. 100.