FEASIBILITY STUDY FOR REPLACING ASYNCHRONOUS GENERATORS WITH SYNCHRONOUS GENERATORS IN WIND-FARM POWER STATIONS

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Abstract

Because of the global energy crisis, the unpredictability of the non-ending price fluctuations of fossil fuels and the complexities of construction and maintenance of nuclear power plants, wind energy and utilization of wind farms has gained an increasing importance and interest. Several wind farms are being utilized, the most important of which is the example farm power-station. In this power station, all units have induction generators with gearboxes of various power capacities. In this study, the authors

1. compared synchronous and asynchronous generators of wind farms from the viewpoints of capacity, speed, excitation, independent operation, voltage regulation, power coefficient control, paralleling with electrical power network, impact on the electrical power network during paralleling, cost and power coefficient; and,
2. studied the feasibility of replacing synchronous generators with synchronous generators, particularly the ones with no gearbox, on a test farm.

Of the four generator types—squirrel-cage induction, synchronous with permanent magnet, induction with winded rotor, and synchronous with wired field—the squirrel-cage induction and synchronous with permanent magnet types offer the best advantages to wind-farm power plants. Comparing these two, the synchronous generator with permanent magnet was found to be significantly superior to the squirrel-cage induction generator in terms of higher power coefficient and higher efficiency. Furthermore, it does not require power storage. This study evaluated the replacement options for a test farm as a model power station and reviewed the various major brands of equipment on the global market.

Introduction

A wind-farm power plant generally includes the following:

1. Wind turbine and subassemblies
2. Generators of electrical power
3. Transformers
4. Load regulators for the power plant, independent of the power network
5. Other components such as voltage and frequency regulators, and regulators of mechanical components (brake, direction etc.)

Wind turbines that were originally designed for use in rural areas were directly connected to generators; that is, the generator and turbine had the same revolutions per minute (RPM). In modern systems, the turbine is connected to the generator via a gearbox that allows variable generator speeds, up to four or five times the speed of the turbine, or more in some cases. For example, if the turbine rotates at 100rpm, the generator can have a speed of 400rpm. While this reduces the generating cost, it increases the weight (and costs) of the wind converter and its tower, and has one-time procurement and annual maintenance costs associated with the gearbox. In comparison to light-weight systems, heavier wind converters cause further difficulties in crane hauling and installation on the tower top. One of the advantages of direct connection of the turbine and the generator is elimination of the gearbox and its maintenance requirements.

In wind turbines, its blades and the generator are generally designed for mounting on top of the tower. A power transmission shaft can be used to have the generator installed at ground level. Wind–farm generators can produce direct or alternating currents. The frequency of the alternating current produced by AC generators is directly proportional to the rotational speed (RPM) of the turbine, and is required to be fixed at 60Hz in the U.S. and 50Hz elsewhere.

For small wind-farm power stations, the cost of a mechanism for keeping the RPMs at a constant level may be prohibitive. Synchronous generators output AC power but are required to meet voltage and frequency standards. This requirement further complicates the design of the turbine blades to operate under varying wind velocities. Today's technology provides generators that are electronically regulated to produce electricity with a constant frequency under variable wind conditions. Through a different method, the generator produces DC current that an inverter converts to AC. In a widely-used method, the generator's DC output is extracted via brushes that contact the commutator of the generator. In yet another method, the generator's AC output is converted to DC via a diode, hence brushes and commutator rings are not used.

Characteristics of an Optimal Generator for Wind-Farm Power Plants

In a wind-farm power plant, the input energy has no sustainable trend, and its variation is dependent on the wind velocity, that is, both direction and speed of the wind. The regulation of these variations for optimizing the power generator's input couple is achieved by changing the blades' pitch angle, gearbox, etc. Therefore, additional equipment is needed to ensure the constancy of the desired characteristics of the output power in changing wind velocities, adding to the weight of the cost factor. In other words, the generator's higher sensitivity to wind variations and resulting effects (tensions) add to the overall cost of the system. Selection of an optimal wind-farm generator requires the following considerations:

1. The generator should be as simple as possible, while tolerating the electromechanical tensions;
2. It should be capable of operating within a wider range of variations;
3. Maximum controllability of the voltage and frequency should be a built-in characteristic of the generator itself;
4. Control systems should be minimally necessary and sufficient and economically justifiable;
5. Minimum requirements for maintenance are needed to be installed at a high altitude; and,
6. Maximum generating power [1].

Based on the previous studies on induction and synchronous AC generators, these kinds of generators are highly suitable for wind-farm power plants.

Comparison of Characteristics of Synchronous and Asynchronous Generators

Both synchronous and asynchronous generators are suitable for wind-farm power plants. However, before selecting a generator, it is mandatory to study the operation of the generator and the status of the host power network of which the generator will be a component. Following is a comparison of the characteristics of each type of generator, with a view of the case that the asynchronous generator is connected to the power network [2].

- Capacity: Synchronous generators are suitable for high capacities, while asynchronous ones that consume more reactive power are suitable for smaller capacities.
- Speed: Higher speeds create no problems other than difficulties in manufacturing synchronous generators with large capacities.
- Excitation: Electrical excitation of synchronous generators requires coils for exciting field, whereas asynchronous ones do not need any coils for excitation because the necessary power for excitation of the armature coils can be drawn from the power network. Synchronous generators with permanent magnets are also free from exciting coils.
- Independent Operation: Synchronous generators can be utilized independently, while the operations of asynchronous ones need to be fed with an exciting current from the power network.
- Voltage Regulation: The output voltage of synchronous generator terminals can be regulated but the voltage of asynchronous generators is always the same as the voltage of the power network.
- Power Factor Control: In synchronous generators, the power factor of the front and rear phases and the reactive power can be controlled. Asynchronous generators works with the power factor of the rear phase and a condenser is required for any correction of the power factor.
- Paralleling With The Power Network: For synchronous generators, this is a complex control that requires regulation of the voltage, frequency and phase. For asynchronous generators, however, the control is simpler as paralleling is done only at the synch speed.
- Impact on the Power Network during Paralleling: For synchronous generators, no impact is generated during connection to the network, but some additional currents will flow in asynchronous generators that produce no voltage before connection to the network necessitating consideration of any drop in the network.
- Cost: The Synchronous generators with an electrical exciter are more expensive than asynchronous ones, but below 750kw, synchronous generators with permanent magnets are less expensive than their asynchronous equivalents. For systems above 750kw, the price is slightly higher but, with respect to other advantages, their use may find long-term economical justification. Another point to be considered is that low-speed asynchronous generators are generally expensive.
- Power Coefficient: The standard power factor of synchronous generators is 90% of the front phase; for induction generators, the power factor is deter-

mined by the wind within 5% to 90% of the rear phase.

Winds can be classified into regular and seasonal types [3]. On our test farm, the wind is a local, strong wind that blows southward from noon to midnight. In this paper, the test wind-power plant was used for comparison and a test case for evaluation of the advantages of synchronous generators over asynchronous ones. The first wind turbines with 500kw power and 37m rotor diameter were installed and commissioned in December, 1994. After ten years, the number of units rose to 50. A new contract has recently been signed for installation of twenty, 660kw units. Specifications of the units are presented in Table 1.

Table 1. Technical Specifications of the New Units

Generator Type	Asynchronous. With Gearbox
Rotor Diameter	4 m
Lower Cutting Speed of the Wind	4 m/s
Upper Cutting Speed of the Wind	25 m/s
Nominal Speed of the Wind	15 m/s
Nominal Power of the Generator	660 kw
Number of Blades	3

Figures 1 and 2 show the trend for installation and capacity expansion from 1995 to 2004.

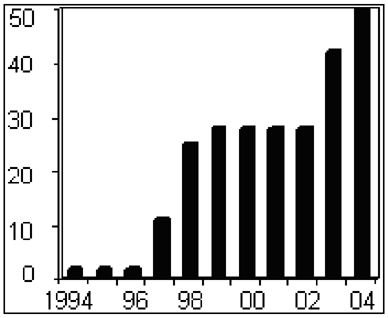

Figure 1. Installed units

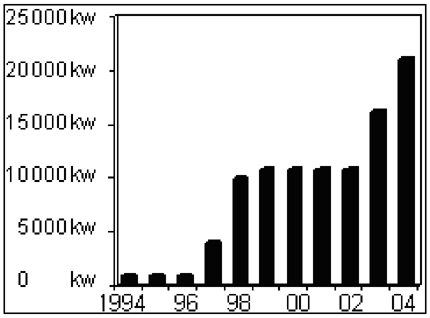

Figure 2. Installed Capacity

On the basis of the above discussion and the general global trend toward synchronous generators, it seems that for wind-farm power plants, synchronous generators with permanent magnets are superior to electrically excited asynchronous ones. This idea is verified by analyzing global trends. All of the existing 50 generators, and even the 20 new ones, are of the induction type and have gearboxes. A survey of maintenance reports clearly indicates that a major part of the maintenance work-load is attributable to breakdowns and faults of the gearboxes.

A comparison of the generators with and without gearboxes shows that those with no gearbox have a larger diameter, shorter length, are approximately of equal weight, and slightly higher price [4]. Currently, the 1,000kw and 3,000kw generators with permanent magnets are available on the international market. In July, 2004, Mitsubishi started operation of the first unit of its wind-farm power plant that utilized a synchronous generator with permanent magnets and no gearbox. It is interesting to note that it has a higher reliability and a lower initial cost. It is also significant that both the technical specifications of this generator and the wind characteristics suitably correspond to requirements and climatic conditions. Besides, the lower cutting speed of the wind for this generator is 2.5m/s, while the existing ones have a lower cutting speed of 4m/s. Table 2 summaries the characteristics of this generator.

Table 2. Specifications of Mitsubishi Generator in Japan

Generator Type	Synchronous Permanent Magnet without Gearbox
Nominal Power	300 kw
Rotor Diameter	30 m
Lower Cutting Speed of Wind	2.5 m/s
Nominal Speed of the Wind	14 m/s
Upper Cutting Speed of Wind	25 m/s

Obviously, this is only one of many choices. Previously, the synchronous generators were disadvantaged in economic terms and initial costs. Today, the permanent magnet synchronous generators with no gearbox in the capacity range of 300-600kw and above 750kw have an initial cost that is only slightly more that the cost of induction generators. In the following, the feasibility of replacing induction generators with multi-pole permanent-magnet synchronous generators is discussed from six different aspects, the first five of which are related to the 20 new generators that are going to be installed in the near future.

A. Initial Cost
B. Efficiency
C. Required surface area
D. Maintenance cost
E. Savings in generating power

A – Initial Cost

The initial cost of a 600kw induction generator with gearbox (Table 2 above) is $263,000 compared to $223,000 for Model A of a permanent-magnet synchronous generator with a nominal power of 750kw. The price of a 1.5Mw Enercon Wind synchronous generator with a permanent magnet was quoted at $577,000. At first glance, this initial cost is twice that of the currently-selected generators, but any comprehensive analysis and comparison needs to consider other factors like efficiency, maintenance costs, reliability, costs of reactive power and, last but not least, the step size for expansion of the total output power. Therefore, in order to upgrade reliability and full utilization of wind energy, the above comparisons are no more than an illustrative example. Despite differences in the price of the gearbox or generator from one vendor to another, one can reliably assume that, currently, the price of any permanent-magnet synchronous generator with up to 750kw of power is below the price of an equivalent asynchronous generator. Figure 3 is a chart of the initial cost [5]-[7].

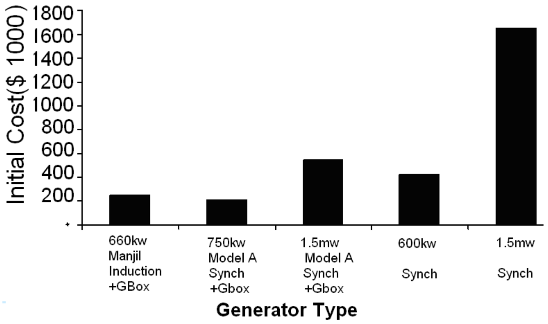

Figure 3. Initial Cost Comparison

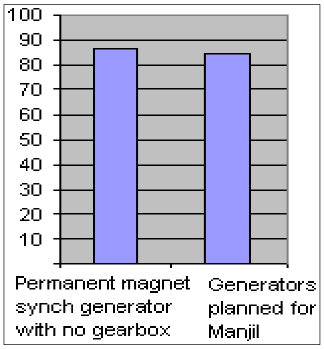

Figure 4. Efficiency

B – Efficiency

The efficiency of an average permanent-magnet synchronous generator with no gearbox is 86.6%, while the efficiency of the 20 variable-speed generators with gearbox induction (planned) is 84.3% (see Figure 4).

C – Maintenance Cost

A major component of maintenance costs comes from the gearboxes. All 20 planned generators will have a gearbox, while a quick review of the product catalogs of various international manufacturers and vendors indicates that the maintenance cost of permanent-magnet synchronous generators with no gearbox is half the cost of equivalent induction generators that include gearboxes; this amounts to a large savings in maintenance costs and another considerable saving by elimination of costly shut-downs due to gearbox breakdown [6].

D – Gain of Generating Power

The following discussion is based on the generator's efficiency. Since 20 units of 660kw will be installed, the total output power will be 13,200kw. Due to the efficiency of the variable-speed gearbox-type induction generators, the effective output of these 20 units will be 11,127.6kw. Permanent-magnet synchronous generators with no gearbox, with equal nominal output power, will yield 11,431.2kw; thus, a gain of 300kw is within reach. If all units are replaced, the gain will be considerable.

E – Surface Area

Following is a discussion of replacing generators with respect to surface area. The diameter of the rotor determines the distance between wind units. Assuming that the 20 units with 4-meter rotor diameters are installed in four rows and five columns, the allowable distance between units, then, is 150 meters. Table 3 shows the technical specifications of an 800kw generator, model E-48.

Table 3. Specifications of an 800kw Generator, model E-48

Generator Type	Synchronous no gearbox
Nominal Power	800 kw
Rotor Diameter	48 meter
Lower Cutting Speed of the wind	3 m/s
Nominal Wind Speed	13 m/s
Upper Cutting Speed of the Wind	28 m/s

A quick calculation indicates that the surface area for the above installation is 675,000m^2. Since the rotor diameter for

800kw generators is approximately equal to 1 rotor diameter of the units, then in the same area of 675,000m^2, 20 units of 800kw generators can be installed that will result in several advantages:

- The initial costs of the new units would be approximately equal to that of the planned ones.
- The total output power will increase from 13.2Mw to 16Mw, a gain of 2.8Mw.
- The new synchronous generators will be free from gearbox maintenance costs, provide higher efficiency and higher reliability, generate no reactive power, and allow larger expansion steps, as discussed earlier.

The replacement of the planned generators with the 2Mw ones will further accentuate the gains (see Table 4) [8].

F – Analysis of Replacement with Identical Output Power

If the 20 units are replaced with units that have power outputs of 2Mw, then only 10 units need to be installed; whereas, if replacement is made with 660kw units, 30 units would need to be installed. Thus, there will be no significant advantages and plenty of disadvantages in terms of maintenance cost, reliability, efficiency and output power index. Besides, the use of induction generators would require capacitors for reactive power, further increasing costs.

Table 4. Technical Specifications of the 2Mw Generator

Nominal Power	2,000 kw
Lower Cutting Speed of the Wind	2.5 m/s
Nominal Wind Speed	13 m/s
Upper Cutting Speed of the wind	20-25 m/s
Generator Type	Synchronous Permanent Magnet without gearbox
Tower Height	60 meters

On January 24th, 2004, this generator began its operation in Japan. Despite the slightly higher initial cost of a permanent-magnet synchronous generator with no gearbox, its numerous advantages make it economically advantageous. Currently, the total installed capacity of the farm, excluding the 20 units that are planned and other expansion plans, is 20,980kw or approximately 21Mw. This consists of 18 units of 550kw, two units of 500kw, 27 units of 300kw, and three units of 6,660kw. Only ten units of the proposed generator can replace the existing 50 units. One proposed unit can replace seven units of 300kw, thereby reducing the maintenance costs.

The present configuration has an output power of 17,203.6kw at an optimistic efficiency of 82%. Using the permanent-magnet synchronous generators that have an efficiency of 86.6%, the output power will increase to 18,168.7kw, yielding a gain of 965kw, nearly a 1Mw increase in capacity. Additionally, the system will be reactive-power-free and not have related capacitor banks. The squirrel-cage generators, with connection to the power network, have a lower power index. Their maintenance costs is t times that of the generators with no gearbox. In summary, the use of permanent-magnet synchronous generators of 1Mw and above is both economically and operationally advantageous, and also why global trends support their use.

Summary and Proposals

This paper considered the power generation of a test farm as a case study, but its conclusions seem to be valid for all wind farm-power stations around the world. Among the squirrel-cage induction generators, induction generators with a coiled rotor, synchronous with a coiled field and synchronous with a permanent magnet, two types are more advantageous for wind farms: the squirrel-cage and permanent-magnet types. The test farm utilized the squirrel-cage type, while the permanent-magnet type had higher advantages, including a higher-power coefficient and efficiency, and elimination of capacitor banks.

Table 5 summarizes the previous discussions about the various generators in the wind farms. Consequently, the following proposals are presented:

- For capacities of up to 750kw, due to lower initial costs, replacement of the induction generators with synchronous generators seems logical.
- Above 1Mw, despite the slightly higher initial costs, the use of synchronous generators seems economically justifiable.
- Since the wind turbines have a 20-year life, it seems advisable to replace the units that are older than ten years, and consider synchronous generators for new installations.

References

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Table 5. Comparison of the Various Generators for Variable Speed Turbines √: Advantage ×: Disadvantage

Squirrel-cage Induction	Induction with coiled rotor	Synchronous with coiled field	Synchronous with Permanent Magnet
√ Simple and Robust	×Complex Structure	×Complex Structure	√Simple and Robust
√Reliable	×Slipping rings for DFIG	×Slipping Rings	√Reliable
√No Slipping Rings	√No Slipping Rings for BDFG	×Regular Maintenance	√No Slipping Rings
√Low Maintenance	High Cost	×High Cost	√Low Maintenance
√Low Cost	×Large and Heavy	×Large and Heavy	√Low Cost
×Low efficiency	√High efficiency with DFIG	√High efficiency in a wide range of load	√Small and lightweight
×Low power coefficient	×Low power coefficient	√High power coefficient	√High power coefficient
×Narrow speed range	√wide speed range	√wide speed range	×Narrow speed range
√Flat Torque	×Wavy Torque	√Wide-range torque	
		√Flat Torque	
Control and Regulation			
		√No need for Capacitors	
×Needs Capacitors	×Needs Capacitors	√Ease of Voltage Control	√No need for Capacitors
×Complex Voltage Control with static generator	×Complex Voltage Control with static generator	√Quick Torque Control	
×VAR or Capacitor	×VAR or Capacitor	√Easy control of Power Coefficient and reactive power	
√Stable operation in Unstable conditions	√Can be used as starter Motor		
√Can be used as starter Motor		√Can be used as recovery break	
Inverter Requirements			
×Large Scale Inverter	√Inverters for 25% to 50% of nominal power	×Large Scale Inverter	×Large Scale Inverter
√One controlling inverter	×Two controlling inverters	√One controlling inverter	√One controlling inverter
√Simple inverter control	×Complex inverter control	√Simple inverter control	√Simple inverter control
1 rectifier + 1 inverter		1 field controller + 1 inverter	1 Rectifier + 1 inverter

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