Paper 129, ENT 204

Feasibility Study for Replacing Asynchronous Generators with Synchronous Generators in Wind Farm Power Stations

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Abstract

Because of the global energy crises, the unpredictability of the non-ending price fluctuations of fossil fuels and the complexities of the construction and maintenance of the 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. This paper attempts to:

1. compare the synchronous and asynchronous generators of the wind farms from the various 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;
2. The feasibility study of replacing for an example farm asynchronous generators with synchronous generators, particularly the ones with no gearbox.

Of the four generator types, namely, squirrel cage induction, synchronous with permanent magnet, induction with winded rotor, and synchronous with wired field, the first two types offer better advantages to wind farm power plants. And comparing these two, the synchronous generator with permanent magnet is significantly superior to the squirrel cage induction generator, in terms of higher power coefficient, higher efficiency. Besides, it does not require power storage. This paper covers the replacement options for an example farm as a model power station and reviews the various equipments of major brands in the global market.

Introduction

A wind farm power plant has components including:

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 of the wind farm like voltage and frequency regulators, and regulators of mechanical components (brake, direction…)

Before going into a comparative analysis of the advantages and disadvantages of the various kinds of generators, each type of generator is briefly described.

The wind turbines that were originally designed for use in rural areas were directly connected to the generators, that is, the generator and turbine had the same revolution per minute. In modern systems, the turbine is connected to the generator via a gearbox that allows variable generator speeds, up to 4 to 5 times the speed of the turbine, or even more. For example, if the turbine rotates at 100 rpm, the generator can have a 400 rpm speed. While this reduces the generating cost, it increases the weight (and costs) of the wind converter and its tower, and has a one-time procurement and annual maintenance costs of 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 on the ground level. Generators of the wind farms can produce direct or alternating currents. The frequency of the alternating current produced by AC generators is directly proportional with the rotational speed (RPM) of the turbine, and it is required to be fixed at 60Hz in US and 50Hz elsewhere. For small wind farm power stations, the cost of a mechanism for keeping the RPM at a constant level may be prohibitive. Synchronous generators output AC power but are required to meet the voltage and frequency standards. This 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 constant frequency under the variable conditions of wind. In a different method, the generator produces DC current that an inverter converts it to AC. In a widely used method, the generator's DC output is extracted via brushes that contact the commutative of the generator. In another method the generator's AC output is converted to DC via a diode, hence brushes and commutations 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 equipments are 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) adds 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 requirement for maintenance is needed to be installed at a high altitude.
6. Maximum generating power [3]

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

Comparison of Some Characteristics of Synchronous and Asynchronous Generators [10]

Both synchronous and asynchronous generators are suitable for wind farm power plants. However, before selecting the generators, 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 on the case that the asynchronous generator is connected to the power network.

- Capacity: Synchronous generators are suitable for high capacities and asynchronous ones that consume more reactive power are suitable for smaller capacities.
- Speed: Higher speeds create no problems other than difficulties in manufacturing of synchronous generators with large capacities.
- Excitation: Electrical excitation of synchronous generators require coils for exciting field whereas asynchronous ones do not need any coils for excitation because the necessary power for excitation the armature coils should be drawn from the power network. The synchronous generators with permanent magnet 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 the synchronous generator terminals can be regulated but the voltage of the 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. The asynchronous generators works with the power factor of 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. But for asynchronous generators, the control is simpler as paralleling is done only at the synch speed.
- Impact on 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 and this necessitates consideration of any drop in the network.
- Cost: The synchronous generators with electrical exciter are more expensive than asynchronous ones, but in the ranges less than 750 kw, the synchronous generators of the with permanent magnet are less expensive than their asynchronous equivalents; and for above 750 kw, their price is slightly higher, nevertheless, 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 the synchronous generators is 90% of the front phase, and for induction generators, the power factor is determined by the wind within 5% to 90% of the rear phase.

4 – Wind Potential Energy in example Farm Before going into details of generator substitution, we need to have an overview of the wind energy in Land.
Winds can be classified into regular and seasonal types [1]. In the example Farm, wind is a local and strong wind that blows southward from noon to midnight,
In this paper, the example wind power plant is used as a comparison and analysis test case for evaluation of the advantages of synchronous generators over asynchronous ones.

5- Analysis of replacement in example Farm Wind Power Plant the first wind turbines with 500 kw power and 37m rotor diameter were installed and commissioned in December 1994. After 10 years, the number of units rose to 50, and presently, a new contract is signed for installation of 20 660 kw units. The specifications of these new units are presented in

Table 1 – Technical Specifications of the New Units

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
Generator Type	Asynchronous with Gearbox
Number of Blades	3

Figures (1) and (2) show the trend for installation and capacity expansion during 1995 to 2004.

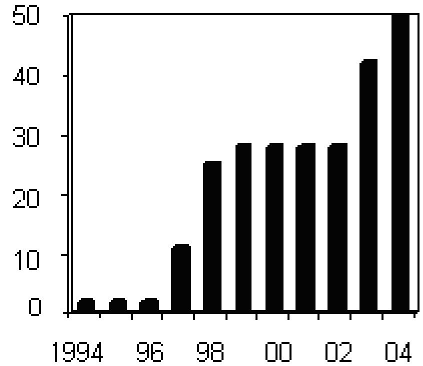

Figure (1)- Installed units

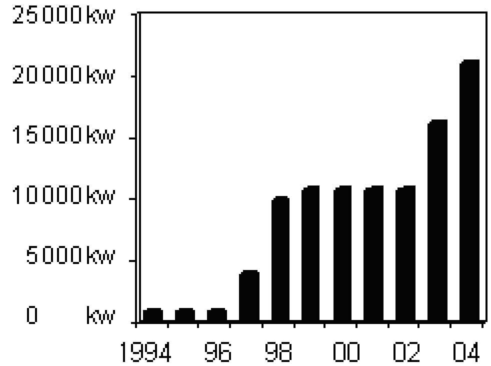

Figure (2)- Installed Capacity

On the basis of the above discussion and the general global trend toward synchronous generators, it seems that for our wind farm power plants, the synchronous generators with permanent magnet are superior to electrically excited asynchronous ones. This is verified by the global trend, too. All existing 50 generators and even the 20 new ones are of induction type and have gearboxes. A survey of the 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 gearbox shows that those with no gearbox have a larger diameter, shorter length, approximately equal weight, and slightly higher price [11].

Presently, the 1000 kw and 3000 kw generators with permanent magnet are available in the international market. In July 2004, Mitsubishi started the operation of the first unit of its wind farm power plant that utilized a synchronous generator with permanent magnet and no gearbox. It is interesting that it has a higher reliability and a lower initial cost. It is quite 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 2.5 m/s while the existing ones have a lower cutting speed of 4 m/s. Table 2 summaries the characteristics of this generator.

Table 2 – Technical 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 the Wind	2.5 m/s
Nominal Speed of the Wind	14 m/s
Upper Cutting Speed of the Wind	25 m/s

Obviously, this is only one of the 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 300-600 kw and above 750 kw 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:
This analysis is related to the 20 new generators that are going to be installed in near future. The six aspects are:

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

A – Initial Cost
The initial cost of 600 kw induction generator with gearbox (Table 2 above) is USD 263000 compared to USD 223000 for Model A of permanent magnet synchronous generator, while the nominal power of this one is 750 kw. The price of a 1.5 mw Enercon Wind synchronous generator with permanent magnet is quoted as USD 577000. A first glance indicates that its initial cost is twice the cost 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, many other factors, 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 the wind energy, the above comparisons are no more than an illustrative example. Despite differences in price of gearbox or generator from one vendor to another, we can reliably assume that currently, the price of any permanent magnet synchronous generator with 750 kw power or less is below the price of an equivalent asynchronous generator. Figure (3) is a chart of the initial cost [13], [12], [8].

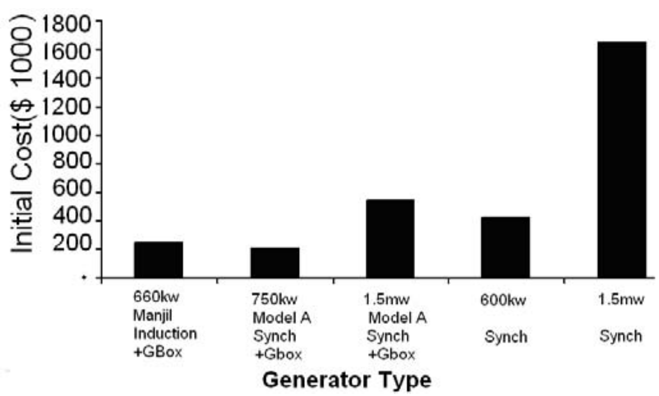

Figure (3) - Initial Cost Comparison

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 with gearbox induction generators (planned) is 84.3%. See Figure 4.

ISBN 978-1-60643-379-9

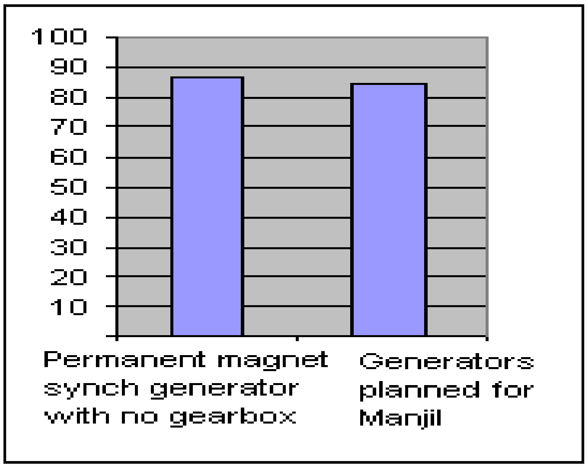

Figure (4) – Efficiency

C- Maintenance Cost [12]

A major component of the maintenance costs comes from the gearboxes. All 20 planned generators will have 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; and this amounts to a large saving in maintenance costs and another considerable saving by elimination of costly shut-downs due to gearbox breakdown.

D- Gain of Generating Power

The following discussion is based on generator's efficiency. Since 20 units of 660 kw will be installed, the total output power will be 13200 kw. Due to efficiency of the variable speed gearbox type induction generators, the effective output of these 20 units will be 11127.6kw. Permanent magnet synchronous generators with no gearbox, under equal nominal output power will yield 11431.2 kw, thus a gain of 300 kw is within reach.

If all units are replaced, the gain will amount to a highly considerable sum.

E- Surface Area

Following is a discussion of replacing generators with respect to surface area. The diameter of rotor determines the distance between wind units. Assuming that the 20 units of 4-meter rotor diameter are installed in 4 rows and 5 columns, then the allowable distance between units is 150 meters. Table 3 shows the technical specifications of a 800kw generator model E-48.

Table 3 the technical specifications of a 800kw generator model E-48

Generator Type	Synchronous, no gearbox
Nominal Power	800 kw
Rotor Diameter	48 me3ter
Lower cutting speed of the wind	3 m/s
Nominal wind speed	13 m/s
Upper cutting speed of the wind	28 m/s

ISBN 978-1-60643-379-9

An arithmetic calculation indicates that the surface area for the above installation is 675000 square meters. Since the rotor diameter for 800kw generators are approximately equal to 1rotor diameter of the units, then in the same area of 675000 m^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 rise from 13.2 mw to 16 mw, which is 2.8 mw more.
- 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 planned generators with 2mw ones will further accentuate the gains

F- Analysis of Replacement with Identical Output Power

If the 20 units are replaced units that have a 2mw output power, then only 10 units need to be installed, while replacement with 660 kw units, 30 units need to be installed. Thus, there will be no significant advantage 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 at an additional high cost.

Table 4 -Technical Specifications of the 2mw Generator [6]

Nominal Power	2000 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 Jan 24th, 2004 this generator began its operation in Japan. Despite the slightly higher initial cost of permanent magnet synchronous generator with no gearbox, its numerous advantages make it economically advantageous. Presently, the total installed capacity of the Farm, excluding the 20 units that are planned and other expansion plans is 20980kw or approximately 21 mw. This consists of 18 units of 550kw, 2 units of 500 kw, 27 units of 300kw, and 3 units of 6660kw. Only 10 units of the proposed generator can replace the existing 50 units. One proposed unit can replace 7 units of 300kw, thereby reducing the maintenance costs. Present configuration has a output power of 17203.6 kw at an optimistic efficiency of 82%. Using the permanent magnet synchronous generators that have an efficiency of 86.6%, the output power will raise to 18168.7kw, giving a gain of 965kw quite near to a 1mw capacity that is not negligible. Besides the system will be reactive power free and related capacitor banks. The squirrel-cage generators, in 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 that is why the global trend supports their use.

Summary and Proposals

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

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

- In the range below 750kw, due to lower initial costs, replacement of the induction generators with synchronous generators seems quite logical.
- In the range of 1mw and above, 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 10 years, and consider synchronous generators for new installations.

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

References

[1] Aminian, H. and Rezaei, M.H.; "*A Survey of Using New Energies in Iran*"; Power and Water University of Technology March 1993

[2] Khalaji Assadi, M and Safaei, B.; "*A Technical and Economical Evaluation of Wind Farm Power Plants of Iran*"; 10th International Electrical Conference Tehran, Nov. 2001

[3] Khosh Sowlat, A.H.; "*Optimal Selection of Wind Farm Power Generators*"; Power and Water University of Technology, May 1997.

[4] Akbari Sani, M. and Khaluzadeh, H.; "*Evaluation and Comparison of Constant- and Variable-speed Turbines for Optimization of DizBad Wind Farm Power Plant*"; 10th International Electrical Conference Tehran, Nov. 2001

[5] www.mitsubishi.org

[6] www.enercon.de

[7] R.Fathiyah,R.Mellott,M.Panagoda; "*Windmill Design Optimization Through Component Costing*"; IEEE seminar London July 2000

[8] C.Veganzones N.Fransisco Blazquez, D.Ramirez ; *"Guidelines for the Design and Control of Electrical Generator System for new Grid Connected Wind Turbine Generators"*; E.T.S Engineers Industrials. June 2004

[9] A.Grauers; *"Synchronous Generators And Frequency Converters In Wind Turbine Applications*"; Technical Report No 175L.May 2002

[10] J. Kean; "*Electrical Aspects of Wind Turbines*".March 1998

[11] Fathiyah, Mellott, Panagoda; *"Windmill Design Optimization Through Component Costing*"; IEEE Seminar London July 2000.

[12] Winwind catalogue

[13] E. Spooner*; "Case study-Direct Drive Wind Turbine Generators*"; IEEE seminar London, July 2000

[14] Chang, Wang; "*Application of Finite Element Method in Design of a 50 kw Direct Drive Synchronous Generator for Variable Speed Wind Turbine*"; Department of Electrical & Computer Engineering, University of New Brunswick June 2001

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