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Design of Grid-Connected Induction Generators for Variable Speed Wind Power Generation

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Abstract – *Commonly standard induction machines are used for both constant speed (CS) and variable speed (VS) wind power generation. But the operational conditions of an induction machine for VS wind power generation are different from CS wind power generation and motor applications. This paper considers the operating condition of VS wind energy conversion system (WECS) in maximum power tracking mode for the exclusive design of squirre-cage induction generator for VSWECS. In such a case, the induction machine always operate at a point close to the maximum torque and maximum efficiency. As a result, these maximums can be introduced to the sizing equations in place of conventionally defined rated efficiency, power factor and starting torque. This design strategy leads to downsizing of induction machine without sacrificing its capacity and performance. Evolutionary programming in MATLAB 6.5 platform was used as a design optimization tool.*

Keywords – Evolutionary programming, grid-connected squirrel-cage induction generators, no-load losses, optimum slip, reactive power size.

1. INTRODUCTION

Most of the specialists working in the field of energy are in agreement with the fact that the renewable energy sources have a key role to play in solving the world energy problem. Among these, wind energy could contribute significantly due to its free, clean and renewable character; besides, it has an extremely large potential. An upper limit for the utilization of the earth's wind supply is essentially to be 1.3×10^{11} KW [1].

A wind energy conversion system (WECS) consists of a wind turbine coupled to the generator shaft by means of a suitable gear box. The generator may be connected to the constant frequency power grid or it may supply an isolated load. On this basis, WECS may be broadly classified as grid-connected or isolated WECS. While use of isolated WECS is restricted to small-scale power generation in remote areas, grid-connected systems are more popular and much high power capacities are commercially available.

Traditionally, either grid-connected or isolated wind generation systems used constant speed wind turbines coupled to squirrel cage induction generators or wound field synchronous generators [2].

The recent evolution of power semiconductors and variable frequency drives technology has aided the wide spread acceptance of variable speed generation systems. Variable speed wind turbine generation has been gaining momentum as shown by the number of companies joining the variable speed wind turbine generation market [3].

Due to their ability to operate at tip speed ratios closer to the optimal values, variable speed wind turbines can produce 8% to 15% more energy output as compared to their constant speed counter parts [4].

Variable speed wind turbine control using cage rotor machine was reported by [5]. The generator was run in V/F mode by a voltage source inverter. The frequency command was decided by the present rotor speed and target power. The turbine speed is measured and the target power is determined based on a cubic function of speed. The required frequency was then computed depending on the machine parameters.

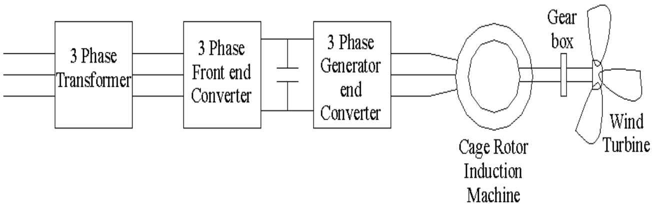

Fig. 1. Schematic representation of variable speed wind turbine

2. WIND TURBINE CHARACTERISTIC AND THE PRINCIPLE OF MAXIMUM POWER TRACKING IN VARIABLE SPEED OPERATION

Wind turbine is characterized by its power-speed characteristics. The amount of power P_t that the turbine is capable of producing depends upon its dimensions, blade geometry, air density and wind velocity.

$$P_t = 0.5\, C_P\, \rho\, A\, V^3 \qquad (1)$$

Where, ρ is the air density
A is the swept area of the turbine
V is the wind velocity

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C_P is called the power coefficient and is dependent on the ratio between the linear velocity of the blade tip (ω_t. R) and the wind velocity (V). This ratio known as the tip-speed ratio defined as:

$$\lambda = \frac{\omega_t \times R}{V} \tag{2}$$

Where, R is the radius of the turbine
ω_t is the angular velocity of the blade tip

An idealized C_P vs. λ curve taken from [6] is shown in Figure 2. It is observed that the power coefficient is maximum for a particular tip-speed ratio.

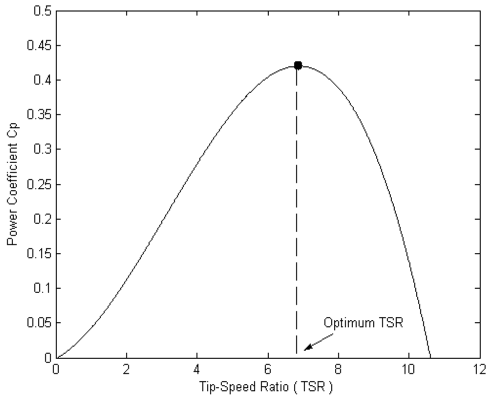

Fig. 2. Tip-speed ratio vs. power coefficient

This implies that for any wind velocity there is a particular rpm for which maximum power transfer takes place (Figure 3). The prime motivation for variable speed control of WECS is to track this rotor speed with changing wind velocity so that C_P is always maintained at its maximum value. Using the C_P vs. λ curve, the power speed characteristics are plotted by using MATLAB program.

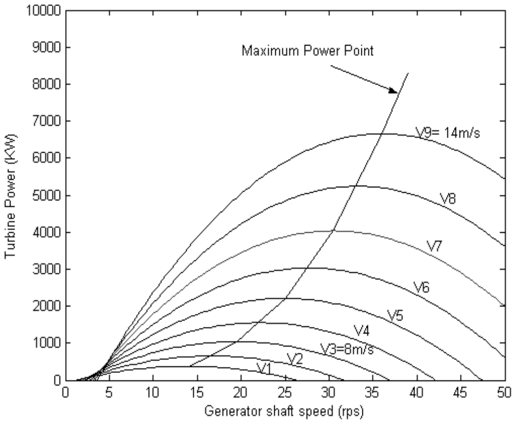

Fig. 3. Turbine power-generator shaft speed characteristics

3. DESIGN OF VARIABLE SPEED INDUCTION GENERATOR

For the variable speed drive systems, the ongoing trend is development of solid-state converters and control algorithms, and the induction machines themselves had not gone through any profound changes compared to the solid-state converter counter part within the same system.

The induction machine for the constant speed WECS connected to the grid directly and work with fixed voltage and frequency. However, the induction machine used for variable speed WECS works with variable voltage and frequency and connected to the grid through inverter arrangement.

Thus, the operational conditions of an induction machine for variable speed wind power generation are different from constant speed wind power generation and motor applications.

This implies that the design of induction machines for variable speed grid connected wind power generation should be reconsidered to make them more suitable for their operational conditions.

4. DESIGN STRATEGIES

In variable speed WECS, the shaft speed may vary over a wide range from cut in wind speed to cut out wind speed. Due to the wide range of speed variation in the useful operating range of wind turbines, the machine size needs to be kept larger than commercial machines of the same rating and number of poles. It is observed that the power rating of the generator in the variable speed scheme is five times greater than that of the optimal version of the constant speed case.

If the shaft speed is kept in a relatively narrow range, a custom-designed squirrel-cage induction generator offers a solution.

Operating the generator over a wide speed range may result in a considerable reduction in over all efficiency of the energy conversion process. Since the generator efficiency varies over a wide range with shaft speed.

Efficiency can be increased by optimizing the operating slip frequency by choosing the proper voltage and frequency.

Considering the design strategies of generator as in [8] and the operation of variable speed WECS with inverter allows the stator and rotor slot numbers, shape and size to be optimized exclusively for minimizing the leakage inductance and resistance. In general, the effective utilization of rotor slot area can be increased, consequently the advantages associated with the reduced rotor leakage inductance and resistance, such as increased peak torque, improved efficiency and power factor can be expected.

In maximum power tracking operation of variable speed WECS the induction machine is always operated at a point close to the maximum torque, maximum efficiency and improved power factor (using front end converter). As a result these maximums can be introduced to the sizing equations, in place of the starting torque, the conventionally defined rated frequency and power factor.

The new design strategy has the potential to downsize the induction machine by about one or two frame size, without sacrificing its capacity and performance.

Apart from the above strategies, the following strategies which are explained in [8] for constant speed WECS are also applicable to variable speed WECS.

In wind power plants generally no-load losses are undesirable, since they make it more difficult to convert small wind speeds into electrical output and increases the non rotational time of the turbine generator. However, induction machines as generators normally achieve larger induced voltage and thus larger saturation states in normal generation than in motorized operation. This leads to increase in no load losses and poor power factor values. Therefore the generator should be designed for small no-load losses.

5. MAJOR DESIGN EQUATION

The D^2L equation has been used for decades to size electrical machinery. This equation written for motor operation, is $hp/n_s = C_0D^2L$. The equation relates power output hp and synchronous speed n_s to the rotor volume through an output coefficient C_o. The D^2L sizing equation is found by simultaneous solution of following set of equations:

$$E = 4.44 fN_1K_W\phi\times10^{-8} \quad (3)$$

$$B_g = (\frac{\pi}{2})[\frac{\phi}{(\pi DL/p)}] \quad (4)$$

$$hp = m_1VI_1\eta\cos\theta/746 \quad (5)$$

$$K_1 = \frac{2m_1N_1I_1}{\pi D} \quad (6)$$

$$f = \frac{pn_s}{120} \quad (7)$$

Which gives $\frac{hp}{n_s} = C_0D^2L$ (8)

Where, C_O is the output coefficient = 0.1558 Bg K_1*10^{-11}

B_g is the flux density in the air gap
m_1 is the number of phases
N_1 is the turns per phase
K_1 is the surface current density
K_w is the winding factor
D is the diameter of the rotor
L is the length of the rotor

It has been found worthwhile to re-examine the sizing procedure since the D^2L equation does not consider several key factors. For example, machine size is affected by the complete stator geometry which includes the relative proportions of the stator inner and outer diameters, slot and tooth dimensions, flux densities in the iron parts and the actual current densities in the conductors. The output coefficient C_o in the D^2L equation contains only the air gap quantities of flux density and surface current density. There are no relationships connecting these air gap quantities with the flux and current densities existing in the machine's interior.

The above deficiencies are eliminated by using the equations developed in the paper [7]. The equation which relates stator geometry to the flux distribution in the air gap, stator teeth and stator core defined by the following equation:

$$a[\frac{D_i}{D_O}]^2 - 2b[\frac{D_i}{D_O}] + 1 = \frac{S_sA_{cu}}{(\frac{\pi D_O^2}{4})K_{cu}} + \frac{\delta_1}{D_O^2} \quad (9)$$

Where, A_{cu} is the conductor area in each slot
D_i is the inner diameter of the stator
D_o is the outer diameter of the stator
a and b are the flux density coefficients
S_s is the number of stator slots
δ_1 is the quantity accounts for the variation in slot shape

To include the effect of magnetic and electric loading in the Equation 9 the following constraints are introduced:

$$E = 4.44 fN_1K_W(\frac{2D_iL}{P})B_g\times10^{-8} \quad (10)$$

$$hp = m_1VI_1\eta\cos\theta/746 \quad (11)$$

$$J_1 = \frac{2m_1N_1I_1}{S_1A_{cu}} \quad (12)$$

$$f = \frac{pn_s}{120} \quad (13)$$

where J_1 is the current density in stator slots.

The copper area is constrained to follow restrictions placed on the current density in stator slots J_1, the air gap flux density is directed to take on values compatible with voltage, number of turns etc.

Using the set of Equations 10 to 13, Equation 9 is modified and rearranged to get the sizing equation as:

$$\frac{P_O}{n_s} = f(\lambda)D_O{}^3L \quad (14)$$

where the output coefficient f(λ) is:

$f(\lambda) = C_1\,B_g\,J_1\,K_{CU}\,S_S\,K_W/K_E\,\eta\,\cos\Phi\,(a\lambda^3+b\,\lambda^2+c\,\lambda)$

C_1 is a constant
K_{CU} is the ratio of conductor area to slot area
K_E is the voltage factor
λ is the ratio of inner to outer diameter of the stator

The coefficients a, b, and c can be expressed as follows:

$$a = [\frac{\pi}{S_S+\pi}(G_t+G_C)]^2(\frac{S_S}{4\pi}+\frac{\pi}{8}) - [\frac{\pi}{S_S}(1-G_t)]^2\frac{S_S}{4\pi}$$

(15)

$$b = -(\frac{\pi}{S_S+\pi})^2(G_t+G_C)(\frac{S_S}{2\pi}+\frac{\pi}{4}) \quad (16)$$

$$c = (\frac{\pi}{S_S+\pi})^2(\frac{S_S}{4\pi}+\frac{\pi}{8}) \quad (17)$$

Where G_t is the ratio of flux densities in the air gap and stator teeth. G_c is the ratio of flux densities in the air gap and stator core.

The output, Equation 14, contains maximizing function f (λ) which considers the iron flux densities and conductor current densities. As long as the coefficients a, b and c are determined, f (λ) is a third order function of λ. Therefore, a suitable value of λ can be figured out by solving the third order equation to obtain the maximum value of $f(\lambda)$ *(i.e.)* maximum output power.

6. OPTIMIZATION PROBLEM

The design of electrical machines is an iterative process, wherein the assumed data may have to be varied many times to arrive at the desired design. The values of variables are changed to satisfy both the performance and cost constraints. Optimization of variable speed grid connected induction generator aims to downsize the induction machine to reduce no-load losses, to reduce reactive power consumption and to reduce the operating slip in order to improve the efficiency further. In the design, a number of physical parameters can be considered for modifications. Fortunately, some may be assigned fixed values, because they have little influence either on the objective functions or on the specific constraints.

Induction Machine Designed as Motor

Design variables:

1) Flux density (Bav)
2) Ampere conductor loading (ac)
3) Current densities of stator (δs) and rotor bar (δb)
4) Flux density of rotor core (Bcs)

Constraints:

1) Minimum limits on full-load efficiency, full-load power factor
2) Minimum limits on the ratio of starting torque to full-load torque
3) Maximum limits on the ratio of starting current to full-load current
4) Stator temperature rise and flux density between stator and rotor teeth

Induction Machine Designed as Variable Speed Induction Generator

Design variables:

The same as motor design

Constraints:

1) Minimum limits on full-load efficiency, full-load power factor
2) Stator temperature rise and flux density between stator and rotor teeth
3) Minimum air gap length

The constraints on start up characteristics which are imposed for motor design are completely ignored because of operation of variable speed grid-connected induction generators with self starting (horizontal axis) wind turbines. Since the optimum design aims to reduce the no load loss and reactive power consumption also the constraints on air gap length is introduced.

7. RESULTS AND DISCUSSION

Table 1 refer to the various design specifications used for the analysis. Table 2 gives the optimized design results of grid connected variable speed induction generators for the four given specifications, designed both as a variable speed induction generator (VSIG) and as a motor.

Figures 5, 6, and 7 represent the diameter and volume reduction, overload capacity and efficiencies of the induction machines designed as motor and VSIG against rating of the machine.

Table 1. Design specification of the machine

	Machine 1	Machine 2	Machine 3	Machine 4
Output (KW)	50	100	225	500
Rated Voltage (V)	400	400	400	690
Sync. Speed (rpm)	750	750	1000	1500
No. of Pole Pairs	4	4	3	2
No. of Phases	3	3	3	3

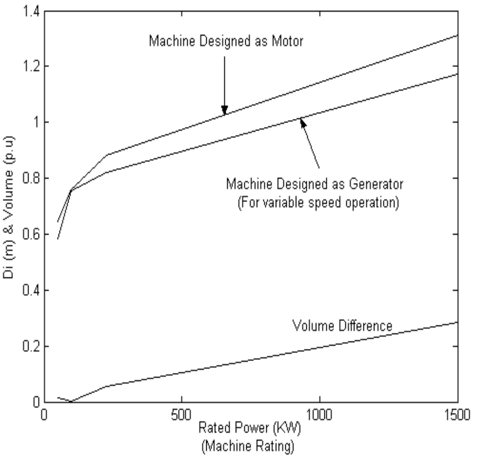

Fig. 5. Rotor inner diameter and volume reduction vs. power rating

Table 2 indicates that motor design on stator outer diameter, inner diameter, total length and rotor diameter are all decreased for the VSIG design. This leads to reduction in volume of the machine for variable speed generator design compared to the motor design as in Figure 5. Also it is observed from Figure 5 that the rated power of the variable speed generator design is substantially larger than that of conventionally designed motor. In the figure, the percentage volume reduction is defined as:

$$\Delta V = \frac{V_1 - V_2}{V_1} \times 100\% \tag{18}$$

where V_1 is the volume of the machine in conventional motor design and V_2 that in generator design for variable speed operation. The figure also indicates that with the increase of power rating, the percentage volume reduction gets larger.

With no considerations given to the starting characteristic for the VSIG design, it is observed that the rotor slot is inevitably shorter and wider than in the motor design. The wider and deeper stator slots of the VSIG design results in less iron area which leads to small no-load loss which is observed from Figure 8.

It is observed from Figure 9 that the slip at the rated power of the VSIG design is smaller than that of conventional motor design. The reduction is more significant for low power ratings.

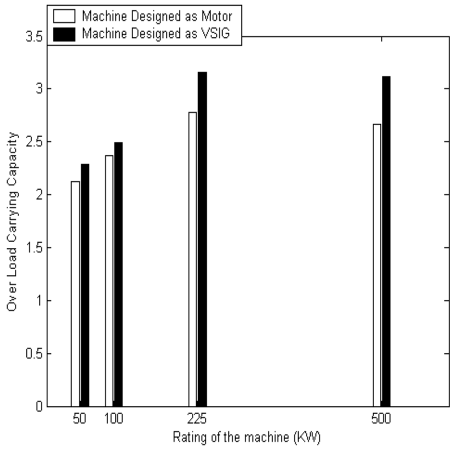

Fig. 6. Comparison of over-load carrying capacity

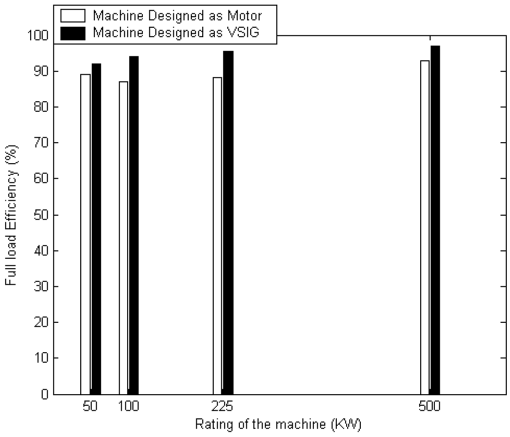

Fig. 7. Comparison of full-load efficiencies

Table 2. Optimal design results for various ratings of squirrel-cage induction machine

Machine Ratings	50 KW	50 KW	100 KW	100 KW	225 KW	225 KW	500 KW	500 KW
Machine Designed As Design Data	Motor	VSIG	Motor	VSIG	Motor	VSIG	Motor	VSIG
Stator Design								
Outer Diameter (m)	0.6286	0.5637	0.8029	0.7593	0.862	0.7348	0.8788	0.8061
Inner Diameter (m)	0.4881	0.4446	0.6597	0.5966	0.706	0.5536	0.6746	0.5
Total length (m)	0.1917	0.1746	0.2591	0.2343	0.3697	0.2899	0.5282	0.3927
No. of slots	120	96	144	96	90	90	120	96
Slot Depth (m)	0.0241	0.0302	0.0224	0.039	0.0249	0.0386	0.0285	0.0985
Upper Slot Width (m)	0.0065	0.0093	0.0088	0.0118	0.0174	0.0121	0.0127	0.0118
Inner Slot Width (m)	0.0075	0.011	0.0096	0.0141	0.0189	0.0145	0.014	0.018
Teeth Width (m)	0.0065	0.0055	0.0058	0.0079	0.0075	0.0075	0.0052	0.0048
Slot Pitch (m)	0.0128	0.0146	0.0144	0.0195	0.0246	0.0193	0.0177	0.0164
Turns per Phase	100	112	72	64	45	45	40	32
Conductor Area (mm^2)	11.267	15.233	22.535	45.439	50.703	61.187	65.318	281.68
Temperature Rise (^{0}C)	60.145	57.231	50.984	51.618	46.258	58.561	46.909	54.653
Rotor Design								
Length of Air Gap (mm)	0.8117	0.7572	1.0269	0.9478	1.2217	1.0012	1.3957	1.0862
Rotor Diameter (m)	0.4865	0.4431	0.6577	0.5947	0.7036	0.5516	0.6718	0.4978
No. of Slots	116	92	140	92	87	87	118	94
Rotor Slot Pitch (m)	0.0132	0.0151	0.0148	0.0203	0.0254	0.0199	0.0179	0.0166
Width of Rotor Slots (mm)	3.5	8.5	4.2	7.5	8	8.5	7.5	10
Depth of Rotor Slots (mm)	16	16	15	14	24	15	27	14
Width of Rotor Teeth (m)	0.0074	0.0103	0.011	0.0134	0.0126	0.0181	0.0078	0.0109
Research Parameters								
Average Flux Density (Tesla)	0.52	0.3861	0.4148	0.41	0.3982	0.31	0.3	0.3
Ampere conductors per m	21681	34665	22270	42880	30419	36056	35589	45000
Ct. density of stator conductor (A/mm^2)	5	4.5829	5	2.7658	5	4.3559	5	2
Ct. density of Rotor Bar (A/mm^2)	6.95	4.036	7	5.5575	6.99	4.0912	7	4
Flux Density of Rotor Core (Tesla)	1.2783	1.2	1.2739	1.2	1.2336	1.2	1.2	1.2

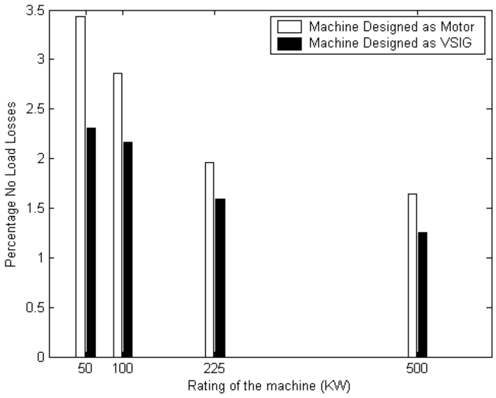

Fig. 8. Comparison of no-load losses

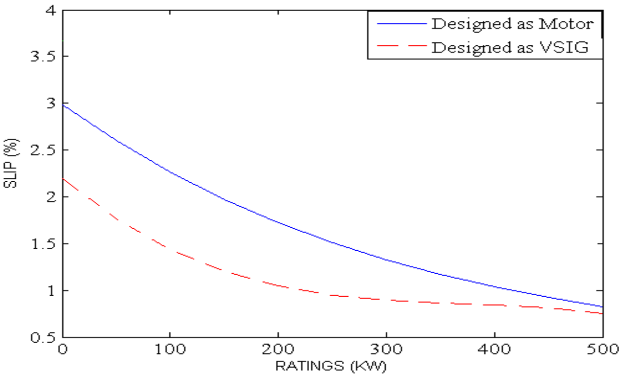

Fig. 9. Comparison of percentage slip

8. CONCLUSION

The main goal of designing an induction machine as a generator for variable speed operation is to realize the reduction in size and increase in overload capacity of the induction machine. Based on the operating condition of variable speed wind energy conversion system in maximum power tracking mode, alternative machine design strategies are proposed.

Corresponding design equations are discussed and investigated. From the above design, it is concluded that if an induction machine is designed as variable speed generator with the above strategies:

- It is possible to increase the output power and reduce the volume of the machine without sacrificing the performance.
- It is possible to reduce the no-load losses. With the reduction in no-load losses, the WECS can be operated at low wind speeds, and hence the operating hours as well as electricity production can be improved.
- It is possible to reduce the operating slip and hence efficiency can be further improved.

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