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WIND ENERGY CONVERSION USING A SELF-EXCITED INDUCTION GENERATOR

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Abstract:

A wind energy conversion scheme using an induction machine driven by a variable speed wind turbine is described. Excitation control has been obtained by employing a single value capacitor and thyristor controlled inductor. Wind speed cube law is proposed to be followed in loading the induction machine for maximising energy conversion. Performance characteristics of the generation scheme have been evaluated over a wide speed range. Harmonic analysis of the proposed scheme shows that harmonic currents and their associated power loss is negligible.

1. Introduction:

Wind energy conversion systems can be mainly classified under constant speed constant frequency (CSCF) and variable speed variable frequency (VSVF) systems. The CSCF schemes which mostly employ synchronous generators tend to be more expensive because of the precise blade pitch control mechanisms required on the wind turbine to maintain constant speed. If a vertical axis turbine, e.g. Derrieus wind turbine is used to drive synchronous machine, it does not have a good speed control mechanism so necessary in such an application.

The VSVF schemes mostly employ an induction machine. In these schemes the need for costly blade pitch control mechanism in horizontal axis turbines is avoided. Also the lack of speed control mechanism for vertical axis turbines does not pose a significant limitation to their use.

The basic characteristics of a VSVF wind energy conversion scheme to supply an isolated ac load are described. A conversion scheme using a controlled inductor in parallel with the capacitor providing the self-excitation is proposed. Because of the use of the controlled reactor, the terminal voltage can be held constant. The constant voltage variable frequency power can be converted to constant voltage constant frequency power using a simple diode bridge for conversion to constant voltage dc and an inverter with very simple firing circuits for constant frequency ac.

The performance characteristics of the proposed scheme over a wide speed range have been investigated and the results are described in this paper. Lagging VArs provided by the inductor to maintain voltage constant with varying speed are controlled by a thyristor bridge. This generates harmonics. The effect of harmonics generated by the converter and rectifier bridge on the generator performance has also been investigated and results are presented in the paper. Harmonic analysis shows that the harmonic component is small and causes a negligible additional power loss.

2. Characteristics of a VSVF scheme:

Self excitation of an induction generator in VSVF schemes is achieved by connecting shunt capacitors across its terminals. The capacitors act as leading VAr source for supplying magnetising current to the machine. The amount of capacitance required for self-excitation varies with speed. Thus if a fixed value capacitor is connected across the terminals of the induction generator, the terminal voltage will vary with speed. In addition, the frequency varies not only with varying speed but also with varying load even at one constant speed.

A scheme to control the VArs in order to maintain the voltage constant at generator terminals under varying speed conditions was proposed in Ref. [1]. This scheme has been implemented [2] by employing a thyristor controlled inductor in parallel with the capacitor. Although, a precise control of terminal voltage was obtained under varying speed conditions, the problem of varying frequency associated with varying load even at one constant speed remained. Thus the scheme implemented in Ref. [2] may not be acceptable over a wide speed range normally associated with windmill applications because of wide variations in frequency.

An obvious choice to circumvent the frequency variation problem is to resort to dc conversion of power generated at constant voltage by control scheme implemented in Ref. [2]. The inverter output can be used as an autonomous supply system.

It was suggested in Ref. [3] that the output of a windmill driven induction generator be converted to dc using a controlled thyristor bridge. If the terminal voltage is held constant as proposed here, a simple diode bridge is sufficient for conversion to dc. The controlled rectification scheme proposed in Ref. [3] has the further limitations that:

1. range of speed is limited by the excessive rise in stator voltage at higher speeds and
2. employing different values of capacitors in different speed ranges is not possible in any autonomous or line connected application of wind energy conversion scheme.

Another important aspect of the VSVF schemes is the efficient energy conversion. It is well known that the power on the wind shaft doubles as the areas swept by blades doubles, but doubling the wind speed increases the power output eight times because the power of the wind turbine varies as the cube of the wind speed. More precisely, the power P developed by a windmill of blade diameter d at a wind speed s is given by the relation [4]

$$P = \frac{1}{8} \rho \pi d^2 C_p s^3 \qquad (1)$$

where ρ is the density of air and C_p is the power coefficient which is the ratio of the shaft power to the wind power.

Fig 1 shows a family of power curves for a wind turbine. If the curve A joining the maximum power points at different wind speeds is closely followed in loading the generator, the turbine-generator system will be most efficient over the entire speed range between cut-in and cut-off speeds. Thus, although a

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pitch control mechanism for a turbine is not necessary in induction generator applications, a mechanism to spill the power above the generator rating is necessary. As demonstrated by Gedser Mill in Denmark, this can be done by designing the airfoil so that blade efficiency falls rapidly as gusting starts [5].

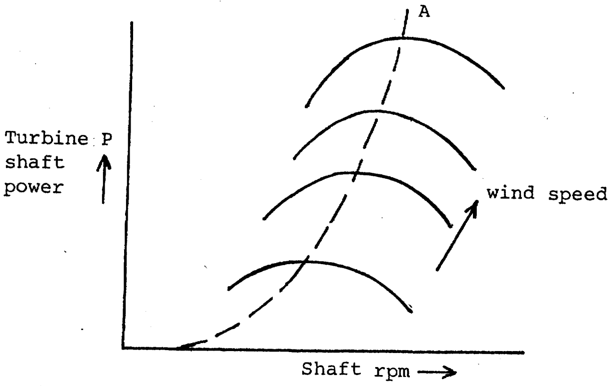

Fig. 1. Characteristics of a wind turbine and generator loading curve.

3. Proposed scheme:

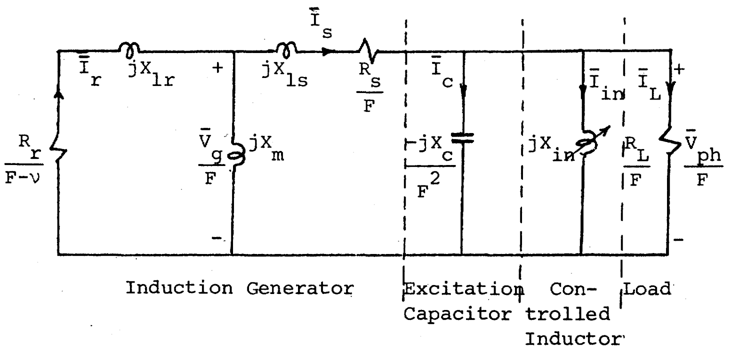

Fig. 3. Steady state fundamental frequency equivalent circuit of the generation system.

Referring to Fig. 2, the bridge rectifier is being loaded by a resistive load and the controlled converter by an inductor (with an extremely small resistance). Therefore, ϕ takes the values of 0 degrees and 87-90 degrees for the rectifier and converter respectively. Thus the rectifier and converter can be simulated to a fair degree of accuracy by a resistor and a variable inductance as shown in Fig. 3.

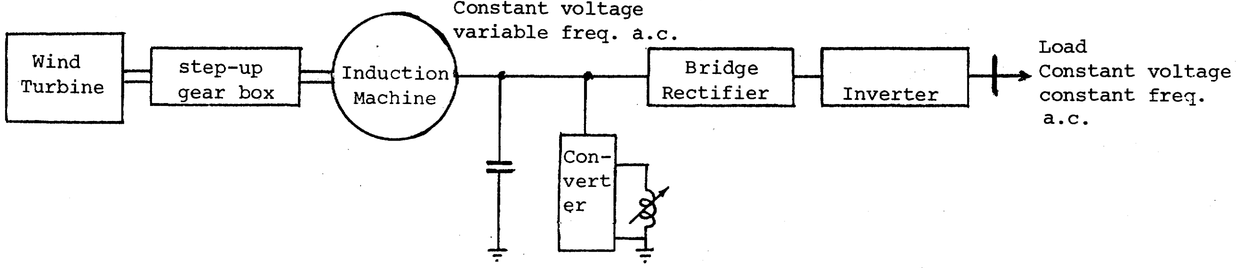

Fig. 2. Variable speed induction generator system with an isolated load using controlled excitation.

The proposed scheme is illustrated in Fig. 2. It employs a squirrel cage induction machine excited by a fixed value capacitor connected across each of its terminals and driven by a wind turbine over a wide speed range. Because of the varying speed, the power generated would have variable voltage and variable frequency. Voltage at the machine terminals can be held constant by employing a thyristor controlled inductor. A diode bridge with an appropriate smoothing reactor connected across the induction machine terminals, thus can give a constant dc output voltage. The fixed dc voltage obtained is independent of the wide frequency variation at generator terminals. The inverter and the load are reflected as a resistive load on the induction generator in the presence of bridge rectifier.

4. Equivalent Circuit Model of the Generation System:

Equivalent circuit of the proposed generation system is shown in Fig. 3. The rectifier load and converter controlled inductor have been simulated on the basis of following ac-dc conversion relations [6].

$$V_{dc} = 1.35\, V_{line} \cos \alpha \qquad (2)$$

$$I_{line} = I_{real} + j\, I_{reactive} = 0.78\, I_{dc} \qquad (3)$$

$$I_{real} = I_{line} \cos \alpha \qquad (4)$$

$$I_{reactive} = I_{line} \sin \alpha \qquad (5)$$

$$\alpha = \phi \qquad (6)$$

Load resistance R_L is determined by eqn. (1) for the wind turbine and can be calculated at any speed N rpm by the relations

$$P_{gen} = K\, (N_{max})^3 \qquad (7)$$

$$R_L = \frac{V_{dc}^2}{K\, N^3/3} \qquad (8)$$

where P_{gen} is the rating of the induction machine, and K a constant, takes into account the gear ratio and other parameters of eqn (1).

The value of exciting capacitor is maximum at the lower limit of the speed range selected and would need to be increased if a significant amount of load was put on the machine at this speed. But because the wind turbine cube law is proposed to be followed for maximum efficiency, the generator will be loaded least at this speed so that a moderately low value of capacitor can be selected. With increasing rpm, the capacitor value doesn't need to be increased even if the load increases in accordance with the cube law.

5. Theoretical Analysis

For the operational equivalent circuit of Fig. 3, the following relation can be written [2]

$$\left(\frac{R_s}{F} + j\, X_{ls} + Z_L + Z_r\right) \bar{I}_s = 0 \qquad (9)$$

$$\text{where } Z_L = \frac{X_{in}\ X_c\ R_L}{F\ X_{in}\ X_c + j(X_{in} - X_c/F^2)\ R_L} \tag{10}$$

$$\text{and } Z_r = \frac{j\ X_m R_r - X_m X_{lr}\ (F - \nu)}{j(X_m + X_{lr})\ (F - \nu) + R_r} \tag{11}$$

Under self excitation conditions

$$\frac{R_s}{F} + j\ X_{ls} + Z_L + Z_r = 0 \tag{12}$$

For any speed ν, eqn. (12) can be solved for X_m and F using Newton-Raphson method with the starting values being taken as the unsaturated value of X_m, and F equal to ν. Using these values of X_m and F, the total performance of the system can be evaluated in conjunction with the measured variation of X_m with Vg/F for the test machine. The value of X_{in} is found by iterating its value till a constant V_{ph} is obtained.

6. Harmonic Calculations:

The equivalent circuit for harmonic calculations is given in Fig. 4. The diode bridge and converter can be represented by two current sources with appropriate phase relationship.

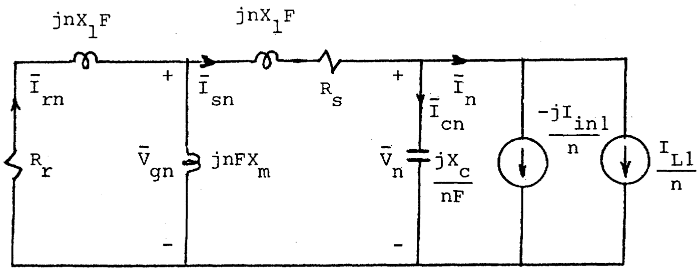

Fig. 4. Steady state harmonic equivalent circuit of the generation system.

Subscript n in Fig. 4 refers to 'n'th harmonic. I_{L1} and I_{in1} are the rectifier bridge and converter currents respectively supplied by the induction generator, and are derived from the performance characteristics at fundamental frequency. From Fig. 4, the harmonic calculations can be performed using the following relations:

$$\bar{I}_n = (I_{L1} - j\ I_{in1})/n \tag{10}$$

$$\bar{V}_n = (ab\ \bar{I}_n)/(a + b) \tag{11}$$

$$\bar{I}_{cn} = (\bar{V}_n \times nF)/(-j\ X_c) \tag{12}$$

$$\bar{I}_{sn} = \bar{I}_n + \bar{I}_{cn} \tag{13}$$

$$\bar{V}_{gn} = \bar{V}_n + \bar{I}_{sn} \times Z_{sn} \tag{14}$$

$$\text{where } a = \frac{Z_{rn} \times jnF\ X_m}{Z_{rn} + jnF\ X_m} + Z_{sn} \tag{15}$$

$$b = -jx_c/nF \tag{16}$$

$$Z_{rn} = R_r + jnX_1F \tag{17}$$

$$Z_{sn} = R_s + jnX_1F \tag{18}$$

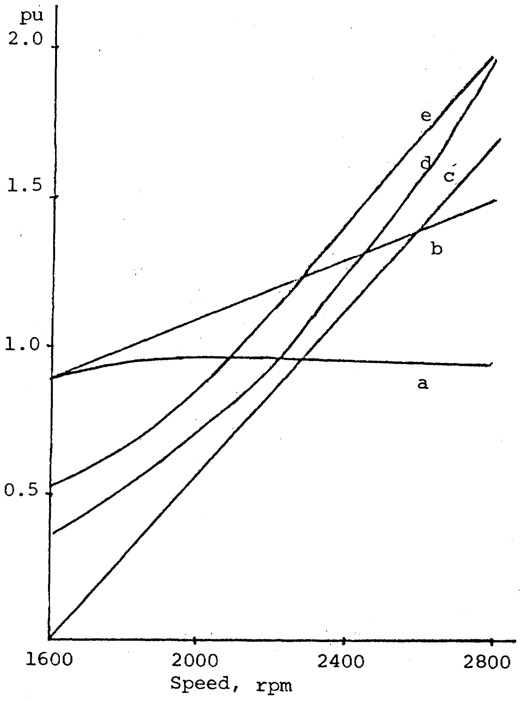

Fig. 5. Performance characteristics of the generation scheme.

a) efficiency of the induction machine
b) F - frequency
c) I_{in} - ac side line current to converter
d) power output of the generator
e) i_c - capacitor current

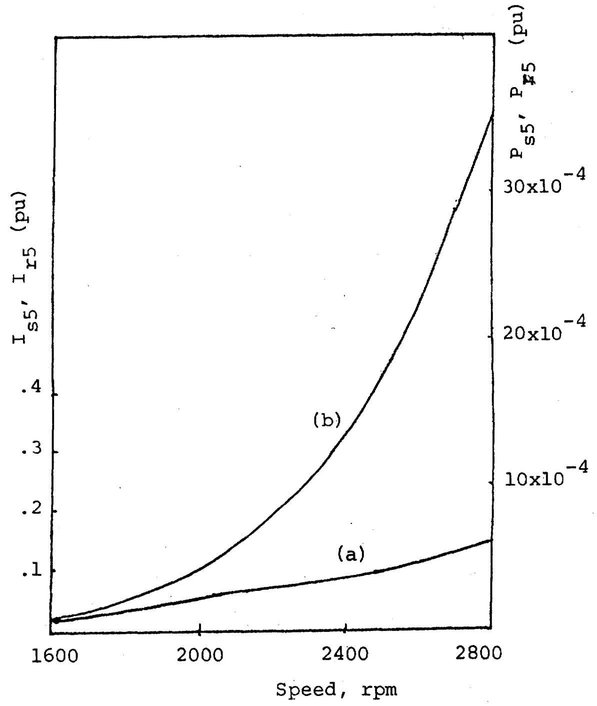

Fig. 6. 5th Harmonic currents and power loss

a) stator and rotor currents
b) stator and rotor power loss

Harmonics generated by the bridge rectifier and converter would be 5th, 7th, 11th, etc. The most predominant harmonics are the 5th harmonic currents in the stator and rotor.

7. Results and Discussion:

The induction generator system with controlled excitation shown in Fig. 2 and modelled in Fig. 3 was simulated. The machine used in the studies was a 5 hp, 4 pole, 60 Hz, 230 V, 14.2A, 1745 rpm squirrel cage induction machine. Parameters and constants for this machine as measured in the laboratory are given below:

Base voltage = Rated phase voltage = 132.79 V
Base current = Rated line current = 14.2 A
Base impedance = Base voltage/Base current = 9.35 Ω
Base power = Base voltage x Base current = 1885.61 watts
Base frequency = Rated frequency = 60 Hz
Base angular frequency = Rated angular frequency = 377 rads/s
Stator resistance per phase R_s = 0.051 pu
Rotor resistance per phase R_r = 0.049 pu
Stator leakage reactance per phase X_{1s} = 0.092 pu
Rotor leakage reactance per phase X_{1r} = 0.092 pu
Unsaturated magnetising reactance per phase X_m = 2.68 pu

Measured variation of magnetising reactance X_m with the air gap voltage for the above machine is given by the relation

$$\frac{V_g}{F} = 1.338 - 0.219\, X_m \qquad (19)$$

Performance characteristics of the induction generation scheme (Fig. 2), as calculated by the method of solution described above, are shown in Fig. 5 for a phase voltage of 0.869 pu. These characteristics are with a constant 225 μF excitation capacitor per phase. The value of 225 μF is based on the capacitance required for self-excitation at the lowest speed of 1600 rpm as used in these studies. As the speed increases, the capacitance required decreases.

It can be seen from Fig. 5 that energy conversion is possible over a wide speed range. The lower limit of the speed range is limited by the value of the capacitor and the upper limit is fixed by the kVA rating of the capacitor as the current flowing through it tends to rise considerably.

Efficiency of the induction machine rises to a maximum and gradually falls but overall remains high over the entire speed range considered. Slip power loss in the rotor is negligible as the slip remains very low over the entire speed range.

The most predominant harmonic currents i.e. the 5th harmonic in the stator and rotor, and the associated harmonic power loss are shown in Fig. 6. It can be seen that the magnitudes of these currents are very low and the corresponding power loss therefore remains extremely low over the entire speed range considered.

8. Conclusions:

The performance of a generation scheme for autonomous applications using self excited induction machine powered by a variable speed wind turbine has been described. The analysis has been done over a wide speed range while loading the machine in such a way that maximum energy conversion is possible. Harmonic analysis of the system indicates that the harmonics generated because of the use of converters are extremely small. The associated power loss is negligible.

The generation scheme seems feasible of application for a wide speed range without employing expensive pitch control mechanisms for the wind turbines. The pitch control mechanism is complex and expensive [7]. Also because of its slow response, the wind turbine blade design has to be improved so that the blades do not go into stall mode during fast changes in wind speed [7]. In comparison, the cost of a diode bridge rectifier and a simple inverter, as required in the proposed scheme, is very small. Also such solid-state devices are highly efficient.

9. Nomenclature:

The symbols used correspond to standard definitions as far as possible. Other symbols not defined earlier are as follows (in pu):

V_g	air gap voltage of the induction machine
V_{ph}	phase voltage on the ac side of the rectifier
V_{line}, I_{line}	line to line voltage and current on the ac side of rectifier
V_{dc}, I_{dc}	dc side voltage and current of the rectifier
I_{real}	real component of I_{line}
$I_{reactive}$	reactive component of I_{line}
$I_s = I_{line}$	stator current of the induction machine
I_r	rotor current of the induction machine
I_L, I_{in}, I_c	ac currents drawn by bridge rectifier, converter and capacitor
α	firing angle in degrees
ϕ	displacement angle in degrees between phase voltage and current
ν	speed
F	frequency
X_{in}	reactance due to converter loaded by inductor
X_1	leakage reactance

10. Acknowledgements

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11. References:

1. Michael B. Brennen and Alberto Abbondanti, "Static Exciters for Induction Generators", IEEE Trans. on Industry Applications, Vol. IA-13, No. 5, Sept/Oct 77, pp. 422-428.
2. O.P. Malik, D. Divan, S.S. Murthy, T. Grant and P. Walsh, "A Solid State Voltage Regulator for Self-Excited Induction Generators", IEEE 1983 Industrial and Commercial Power Systems Conference, Milwaukee, May 1983.
3. D.B. Watson, J. Arrilaga and T. Densem", Controllable dc power supply from wind driven self excited induction machines", Proc. IEE, Vol. 126, No. 12, Dec. 1979, pp. 1245-1248.
4. E.W. Golding, "The generation of electricity by wind power", E. & F. Spon, London, 1976.
5. D.F. Warne and P.G. Calnan, "Generation of electricity from the wind", Proc. IEE, Vol. 124, No. 11R, November 1977, IEE Reviews, pp. 963-985.
6. E.W. Kimbark, "Direct Current Transmission" Vol. 1, John Wiley & Sons, New York, 1971.
7. Richard L. Puthoff, "Status of 100 kW experimental wind turbine generator project", Proceedings of the 2nd Workshop on Wind Energy Conversion Systems, Washington, 1975, pp. 21-36.