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Variable Speed Cage Machine Wind Generation Unit

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Abstract: A comprehensive control strategy, for the variable speed cage induction achine that addresses the control objectives in a wind generation system,i.e.control of the local bus voltage to avoid voltage rise, capture of maximum power in the wind. The control signals are the desired current wave shapes of the rectifier and the inverter in a double–sided PWM converter system connected between the wind generating unit and the grid. Studies performed on a complete model for a variable speed cage machine wind generation unit, including wind profile, wind turbine, induction generator, PWM converter, local load and transmission line. The PWM techniques reduces the harmonics and improves the power factor. Simulation results will be verified using the waveform in the paper. The wave forms at different points in the circuit will be obtained using PSPIECE.

Key words: Induction generators % Power system modeling % Voltage control % Wind energy % Wind power generation

INTRODUCTION

In response to the increasing environmental concerns, more and more electricity is being generated from renewable sources. Harnessing of wind energy as a renewable source to generate electricity has developed extremely rapidly and many commercial wind generating units are now available on the market. The cost of generating electricity from wind has fallen almost 90% since the 1980s. Worldwide installation of wind based generating capacity has exceeded that of nuclear based during recent years—an indication that wind is becoming a competitive player in today's power market. Wind is a variable and random source of energy. Depending on the size of the system, all types of machines, i.e. dc, synchronous, induction, have been used to convert this form of energy to electrical energy. Induction generators are more common and more economical in the range up to 2 MW. Connecting an induction generator directly to a network without any control can be potentially troublesome. It results In sub-optimal performance of the wind turbine and potential Stability problems. Problems with such a simple connection are:

- The magnitude of the voltage at the bus to which the unit is connected may rise unacceptable levels. This is because the existing transmission lines tend to be designed without any consideration for embedded generation.
- Wind turbine output power vs. rotor speed is a nonlinear cubic function. A wind turbine can only deliver maximum possible power at a particular rotor speed. In a simple wind generation system, since the rotor speed is dictated by the electrical system frequency.

To have some level of control on the wind generation unit, various forms of systems can be used. In the simplest form, the wind generating unit is augmented by three-phase passive or active VAr compensators. Using this arrangement, only the terminal voltage can be controlled. Also, despite its being economical and reliable, a VAr compensating system severely limits the energy capture of the wind generating system .In the variable speed constant frequency systems, power electronic devices are used to allow the rotor speed to be changed while the grid frequency is constant. In one scheme, a doubly fed wound rotor induction machine can be used with both the stator and the wound rotor connected to the

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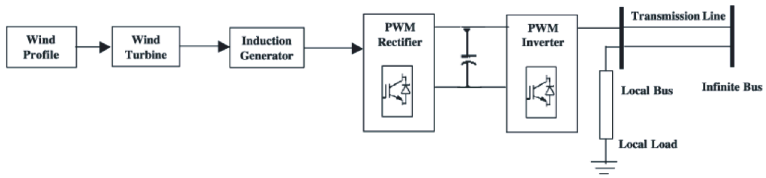


Fig. 1: Simple block diagram of a VSCM wid generation system.

grid. In another scheme, as studied in this paper, a variable speed cage machnie (VSCM) system is used with a rectifier and an inverter interposed between the cage induction generator stator and the grid. The variable speed constant frequency systems have the advantage that the rotor speed can be controlled. This makes it possible to capture maximum energy from the wind turbine. In this paper a comprehensive control strategy is developed in which the voltage rise, maximum power capture from wind is achieved by using only the rectifier and inverter control signals.

VSCM Wind Generation System: A simple block-diagram of a wind generation system is shown in Fig. 1. In this figure, there are five main parts: wind profile, wind turbine, induction generator, power electronics (rectifier and inverter) and the external system (load and transmission line). The modeling of each section is discussed separately and then the overall model is investigated.

Wind Profile: Wind speed changes continuously and its magnitude is random over any interval. To simulate the wind speed, it is common to assume that the mean value of the wind speed is constant for some intervals (for example every 10 minutes). The International Electro-technical Commission has recommended the use of Rayleigh probability distribution for the wind profile to determine the ten-minute mean. To simulate a wind profile, sinusoidal fluctuations are usually added to the randomly changing mean value. A typical expression for the wind velocity is given by, Where x is the random number produced by Monte Carlo simulation. To simulate wind gusts, the magnitude and frequency of the sinusoidal fluctuations is increased. For long term studies (steady state), the sinusoidal fluctuations can be ignored, while for short term studies (transients) the mean can be considered constant.

Wind Turbine: The input of a wind turbine is the wind power (wind speed) and the output is the mechanical power turning the generator rotor. The output power from a wind turbine can be expressed

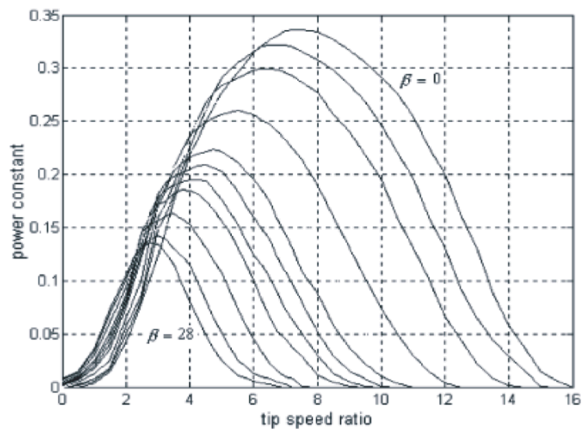


Fig. 2:

$$P_t = 0.5 C_P(l, b).r.A.v^3$$

Pitch angle can be controlled to capture maximum power from the wind and/or limit the aerodynamic power. In this study, since the maximum power is captured by controlling the rotor speed (tip speed ratio) through PWM converter, the pitch angle is only used to limit the input aerodynamic power to the wind turbine. In other words, the pitch angle is kept at zero until the nominal power of the induction generator is reached. At high wind speeds; the pitch angle is increased to limit the input power.

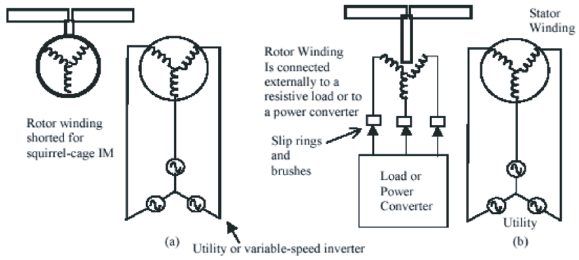
Induction Generator: Currently, the most commonly used generator in wind turbines is the induction generator. Several reasons for using induction generators are:

- Low cost
- Ruggedness

Operates with slip (i.e., with some speed elasticity)

- Readily available in the market in many sizes
- Mature technology

There are two kinds of induction generators used in wind turbines, squirrel cage and wound rotor. Presently, about 90% of utility-grid-connected wind turbines use



Physical diagram of induction generator in WTG applications
(a) Squirrel-cage induction machine
(b) Wound rotor induction machine

Fig. 3:

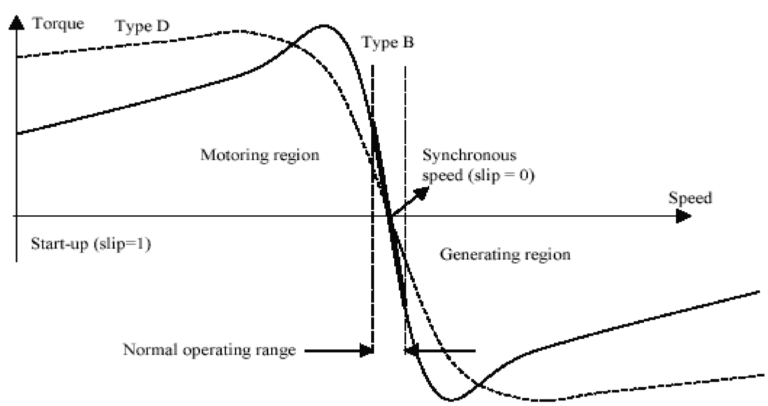
squirrel-cage induction generators. The rotor is made of soft iron with shorted rotor bars of copper or aluminum. They do not need slip rings like a synchronous or wound rotor induction generator. The physical diagrams of a squirrel-cage induction machine (SCIM) and a wound rotor induction machine (WRIM) are presented in Figure 3. The squirrel-cage induction machine has a shorted rotor; therefore, the rotor current is not accessible. Although physically there is no electrical connection between the rotor and stator; the electrical characteristics of the rotor are affected by the stator through magnetic coupling.

With a wound rotor induction machine, the rotor is normally constructed as a three-phase winding with the same number of poles as the stator. Three-phase slip rings (and brushes) are used to allow control of the rotor current.

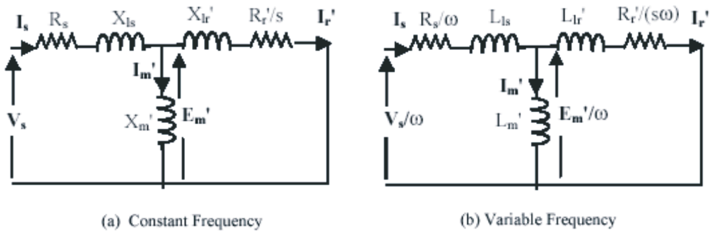
Squirrel Cage Induction Machiner: Figure 4. shows the torque-speed characteristic of an induction machine in the motoring and in the generating region. The National Electrical Manufacturer's Association (NEMA) has established a terminology for four classes of induction machines, Types A, B, C and D. In most applications, type B induction machines (shown in solid line) are used because they give a good starting torque and good efficiency and power factor at rated output. Type D (shown in dashed line) is used when high starting torque is required. Type D has a higher rotor resistance. Typically, the operating region of an induction machine is below 50% of the peak torque. Thus, the operating slip of an induction machine is low (slip < 2 %). Although the operating slip is very low, the induction generator used in wind turbines has the advantage of giving more compliance than a synchronous generator.

Constant Frequency Operation: The equivalent circuit of a squirrel-cage induction generator is shown in Figure 5. The parameters of an SCIM consist of stator resistance Rs, stator leakage reactance Xls, rotor leakage reactance Xlr', rotor resistance Rr' and magnetizing reactance Xm'. The primedsign signifies that the equivalent circuit is referenced to the stator side. Thus, the primedparameter and primed-variable are referenced values and not the actual values. Ideally, the resistances and the leakage reactances are zero and the magnetizing inductance is infinite. In reality, the magnetizing inductance is about 20-50 times the leakage inductance.

During start-up, the slip is one and the rotor circuit branch presents a much lower impedance (almost short circuit) than the magnetizing branch. The starting current is about 5 to 8 times rated current. Although the rotor current is large, the magnetizing current is small. As the rotor speed increases, the slip decreases. The total impedance of the induction machine increases; thus, the stator current decreases and the magnetizing current and the torque increases as shown in the torque-speed characteristic.



. **Torque-speed characteristic of an induction machine at fixed frequency for two different types of machines.**



Equivalent circuit of a squirrel-cage induction generator.

The slip at which the peak torque occurs is approximately:

$$Slip\_peak = \frac{1}{\sqrt{R_s^2 + (X_{is} + X_{ir}^{'})^2}}$$

From the above equation the peak-torque slip can be increased by using a higher rotor resistance (design D).

Power System Connection: To be able to simulate the induction generator and wind generation system, an equation relating Vds, Vqs the stator direct and quadrature axis voltages, to ids, iqs the stator direct and quadrature axis currents, is required. This relationship, required to use a current based power flow grid model, is obtained depending on the configuration of the terminal connection to the load. If the induction generator is connected to a constant voltage bus through a transmission line as well as local load, as shown in Fig. 1, then

$$I = Y.V + \frac{(V - V_B)}{Z}$$

where Z is the transmission line impedance, $Y = (G + jB)$ is local load admittance, V is the terminal bus voltage and VB is the infinite bus voltage, since giving

$$I = i_{ds} + ji_{qs} \quad \text{and} \quad V = v_{ds} + jv_{qs}$$

$$i_{ds} + ji_{qs} = (G + jB).(v_{ds} + jv_{qs}) + \frac{(v_{ds} + jv_{qs} - v_{Bds} - jv_{Bqs})}{(R + jX)}$$

giving the required mathematical relationship between the variables Vds ,Vqs and ids, IQs.

Power Electronics: In many industrial applications , to control of the output voltage of inverters is often necessary to cope with the variations of dc input voltage, to regulate voltage of inverters ,and to satisfy the constant volts and frequency control requirement.

There are various techniques to vary the inverter gain. The most efficient method of controlling the gain is to incorporate PWM control within the inverters. The commonly used techniques are

- Single –pulse-width modulation.
- Multiple – pulse-width Modulation
- Modified –pulse –width modulation.
- Sinusoidal – pulse –width modulation.
- Phase -displacement control

Multiple Pulse-Width-Modulations: The harmonic content can be reduced by using several pulses in each half – cycle of output voltage. The generation of the gating signals for turning on and off of the switches is given by comparing the square wave signal with the high frequency carrier signal .The frequency of the square wave sets the output frequency fo and the carrier frequency fc determines the number of pulses per half-cycle P. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse width modulation (UPWM). The number of pulses per half- cycle is found from,

P = fc/2fo = mf/2

where mf = fc/fo is defined as the frequency modulation ratio.

The rms output voltage can be found from

$V_o = V_s$ (P*/B)^1/2

$m_f = f_c/f_a$

The width of the pulse is given by

* = MTs

where M be the modulation index and it is given by

$M = A / A_c$

where,

A_r be the amplivted of the reference signal

A_c be the amplitued of the carrier signal

Ts be the switching period
The rms value of fundamental component is

$V_1 = 4 * Vs / (2*3.14)^{1/2}$

The output power is given by

Po = Vs^2/R

The rms value of harmonic voltage V_h is

$$V_h = (E_{n=3,5,7}...Von^2)^{1/2}$$
$$= (Vo^2 - Vo1^2)^{1/2}$$

where Vo be the rms value of PWM inverter output voltage and Vo1 be the rms value of fundamental component.

Total harmonic distortion (THD) is = Vh / V01

Main *advantages* include:

- The current or voltage can be modulated, generating less harmonic contamination.
- The power factor can be controlled. The circuit can be built as voltage source or current source rectifiers.
- The power factor can be reversed by reversing the current at the dc link.

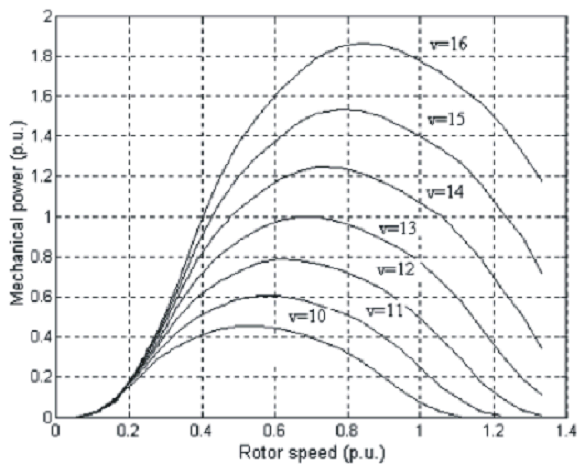
Control Objectives in a Vscm Wind Generation System: The control objective in a VSCM wind generating system is to take into account all control aspects i.e. voltage rise, output power and efficiency. In this section, each aspect is described in detail.

Voltage Rise: The first control objective is to limit the voltage rise. Mostdistribution systems are designed to distribute power from large central power stations. Usually the range of voltage regulators does not extend beyond medium voltage bus bars. Connecting a wind generating unit to a bus bar with no voltage control will change the current flow in the uses and may result in a voltage rise and in violation of limits. To use the wind generation unit safely, either a worst-case scenario is considered or an active voltage control is required. Some of the strategies used in active voltage control are the following.

- Reducing the line impedance by changing the connection point.
- Changing the active power of the local load (load control).
- Changing the reactive power of the grid bus bar. This is mainly accomplished through the use of VAr compensators.
- Changing the reactive power of the wind generator.

This can be achieved by controlling the PWM converters in a VSCM configuration.

Capture Maximum Power: The second control objective is to capture maximum power from the wind. Typical power versus rotor speed relationship of a wind turbine is shown in Fig. 6 for various wind velocities. For a given wind speed, the mechanical output power of the wind turbine is maximum at a particular rotor speed. The best way to control the rotor speed is to change the frequency of the induction machine terminal voltage using the PWM rectifier. The current controlled PWM rectifier allows the change of terminal voltage frequency without affecting the system frequency.



Control Strategy for a VSCM: In this section a hierarchal and comprehensive control strategy is proposed to achieve all the control objectives using the PWM rectifier and inverter based on the VSCM wind generating unit described. The general structure of the proposed controller is shown in Fig. 7. There are three levels in the proposed controller:

Level 1: Given the control objectives (to capture the maximum wind power, to minimize the power loss in the induction generator and to control the local bus voltage at the desired value) and some variables of the wind generating system, calculate the desired rotor speed (wm*), the desired flux and the desired reactive power delivered to or consumed from the grid Q*.

Level 2: Given the desired rotor speed, the desired flux, the desired reactive power and some variables from the wind generating system, calculate the instantaneous input currents to the rectifier and the instantaneous output currents from the inverter for all three phases.

Level 3: Given the desired and measured instantaneous input currents to the rectifier and the desired and measured instantaneous output currents from the inverter, control the PWM converter to guide the system to the optimum conditions.

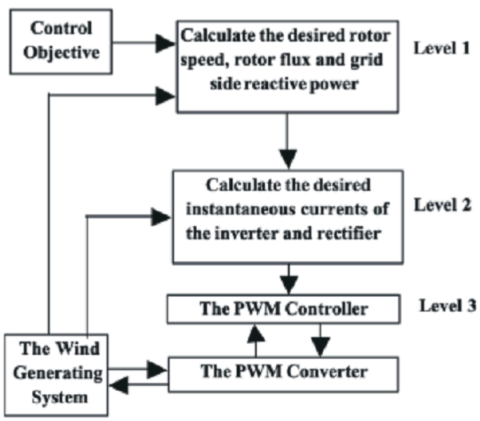
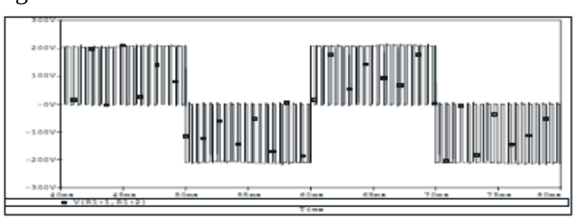
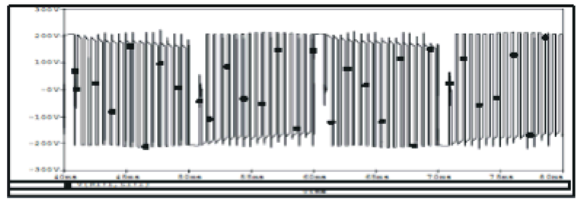


Fig. 7: General control structure

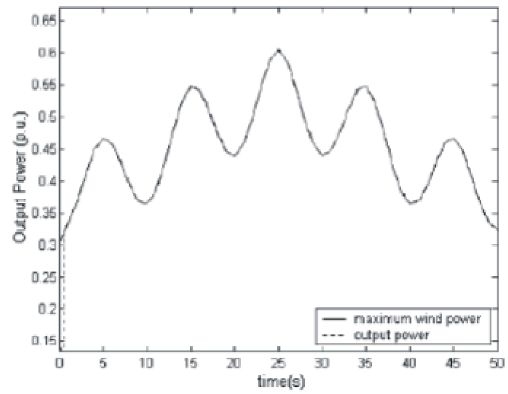


Inverter Output Voltage for R load

System performance as the wind speed is changing is shown in Fig. 8. In this study, the magnitude of the fluctuations was considered to be 5% with periods of 10 and 50 seconds. In this figure the instantaneous voltage in one of the phases, are shown for various load. As can be seen, despite the variation of wind and consequently variation of power and voltage of the induction machine, the grid side bus voltage is well regulated. A plot of the maximum attainable power from instantaneous wind speed and the actual output power of the wind generation system shows the output power closely follows the maximum attainable power.



Inverter Output Voltage for RL load



CONCLUSION

A complete nonlinear model for a variable speed cage induction machine (VSCM) wind-generating unit has been developed. In the model wind profile, wind turbine, induction generator, rectifier, inverter, local load, transmission line and infinite bus have been considered. A hierarchal and comprehensive control strategy for the wind generation system is suggested. The control strategy leads the wind generation system to capture the maximum power from the wind and controls the terminal voltage. All the control objectives are achieved through a double-sided PWM converter. Simulation studies show that the proposed control strategy effectively leads the system to an optimum point.

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