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A CONCEPTUAL FRAMEWORK FOR EVALUATING VARIABLE
SPEED GENERATOR OPTIONS FOR WIND ENERGY APPLICATIONS

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ABSTRACT

Interest in variable speed generating technology has accelerated as greater emphasis on overall efficiency and superior dynamic and control properties in wind-electric generating systems are sought. This paper reviews variable speed technology options providing advantages and disadvantages of each. Furthermore, the dynamic properties of variable speed systems are contrasted with synchronous operation. Finally, control properties of variable speed systems are examined.

INTRODUCTION

The development of wind energy as a viable electric generating option for intertie to electric utility systems dictates total system requirements which include an effective and efficient wind turbine system as well as an acceptable interaction with the electric utility system. Fulfilling both of these needs places significant constraints on the turbine generator design since aerodynamic needs do not necessarily correspond with those of the electric utility system. As a result, a total system approach is required in order to capture essential characteristics to satisfy both needs.

Historically, large horizontal turbine designs have sought a constant speed configuration utilizing a synchronous generator. Such designs tend to minimize mechanical resonance problems. Some vertical axis turbines and many small horizontal axis machines have utilized variable speed arrangements, usually induction generators. Most of these efforts have concentrated on rather simple electrical configurations. In an effort to raise the overall productivity and efficiency of wind turbine systems, recently, attention has been directed to variable speed options for large horizontal axis machines with emphasis on a total wind turbine/generator/utility design. The additional degree of freedom that variable speed provides has to be integrated into a control concept that considers not only the process needs, i.e., the wind turbine and its energy source, but also the total system needs, i.e., the power system and its operation. In the past, most variable speed efforts have utilized available configurations out of convenience rather than developing a system from the "ground floor" for wind energy application. This paper will focus on a conceptual framework for assessing variable speed technology and its application to wind energy with a goal of developing an approach which is an alternative to a synchronous interconnection.

CONCEPTUAL FRAMEWORK

The issue of variable speed electric generating systems must be considered relative to their application to wind energy. Largely, the choice of system and the configuration to date has dwelled on "what's available." A key item for best overall system effectiveness and efficiency is the design of the turbine/generator/utility interface combination. Aeroturbine performance requirements must be coordinated with the design of the variable speed generator. As a result, the turbine generator system, its dynamic interaction with the electric utility system, and the overall control system must be designed as an integrated process. (See Figure 1.)

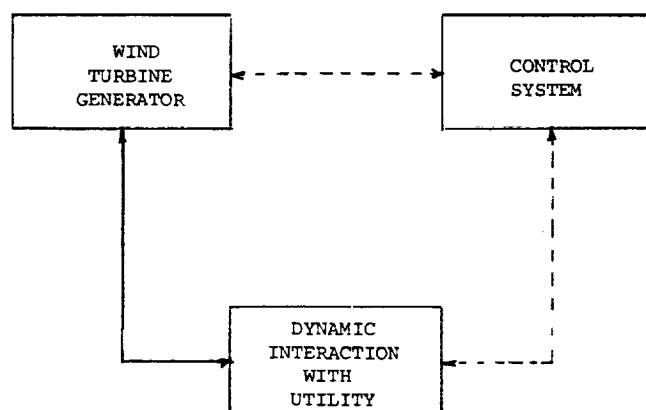


Figure 1. Wind Turbine/Generator/Utility Process

The three conceptual components shown in Figure 1 are key elements of the variable speed system. The solid line represents the natural interaction between wind system and the utility system. The dotted lines represent the control requirements which must shape the turbine-generator response as well as the turbine-generator interaction with the electric system. In an effort to develop future variable speed systems as well as evaluate present designs, the following activities are recommended:

- o Evaluate the variety of converter-variable speed options and assess them for their shortcomings and establish target requirements for new systems.

- o Characterize the dynamic interaction between variable speed systems and electric utility systems.
- o Develop strategy requirements and control systems for various converter-variable speed option for both the turbine-generator pair and its interaction with the electric system.
- o Develop computer models for various converter-variable speed options.
- o Design field tests for the various options to validate the computer models.

VARIABLE SPEED TECHNOLOGY OPTIONS

It is apparent that the number of possible candidate variable speed systems is very large and it is not feasible to cover in detail all such systems. In particular the number of feasible schemes appears to vary inversely as the power rating of the WTG. For additional details on the various options, the reader is directed to Lipo [1].

DC Generator with Line Commutated Inverter Bridge

Probably the most straightforward variable speed system utilizes a DC generator with inversion of the generated DC power to AC by use of a line commutated rectifier bridge. Current flow is in 120 degree blocks at the line frequency on the AC side of the inverter thus requiring filtering at the AC terminals of the bridge to suppress harmonic current flow into the power system and to correct the power factor to unity. Because of the heavy filtering required to eliminate unwanted harmonics of the simple six pulse bridge, other bridge configurations are also in common use. For example, the dual six pulse bridge arrangement results in the elimination of the lowest frequencies, the 5th and 7th harmonics components inherent in simple bridge configurations while halving the next lowest components, the 11th and 13th. An advantage of the dual bridge configuration is that each bridge need only be rated at one-half the KVA rating of the single bridge. It should be mentioned that such alternatives are generic to any of the systems to be discussed which utilize bridge configurations.

While not strictly necessary, some filtering of the DC voltage of the bridge is typically employed so as to minimize stray losses in the generator due to harmonic currents. The simplest type of filter is to simply use a DC link inductor to simply smooth the current. Such systems are said to utilize a DC current link and when the size of the inductor is large the converter-generator system operates much like a current source. An alternative to filtering is to place a capacitor across the terminals of the DC machine and employ a much smaller link inductor which is now selected primarily to limit charging current into the capacitor. In this case the current into the motor is smoothed by providing a low impedance path to harmonic currents. Such a

configuration is said to employ a DC voltage link. When the capacitance is large the converter-generator system appears much like a voltage source to the power system.

It is well known that the power factor of a line commutated bridge varies in direct proportion to the ratio of DC to AC voltage. Hence, in order to maintain good power factor at the terminals of the bridge, the inverter must be controlled such that the voltage on the DC side of the bridge must be maintained constant at its maximum permissible value. In converter terminology such a control is usually called constant extinction angle control in which the inverter is commutated such that the inverter thyristors have just sufficient time to recover blocking ability before forward voltage is reapplied.

Special advantages of this system include:

- o Minimal torque pulsations.
- o Straightforward control algorithm.

Disadvantages of this system are:

- o Maintenance and reliability concerns.
- o DC fault protection.
- o Control response limitations.

Synchronous Generator with Thyristor Rectifier and Inverter

Another class of systems suitable for wind power generation is a synchronous generator supplying power through a DC current link rectifier-inverter. Commutation of the line side inverter is accomplished by taking VARs from the power system. Commutation of the machine side converter is provided by leading VARs from the synchronous machine. In this case, excitation of the machine is by means of a brushless exciter. Electrical generated power must pass through the rectifier-inverter so that the converters must be rated at the full machine rating. One-hundred and twenty degree blocks of current now flow on the AC sides of both the rectifier and inverter. Again, the harmonic content on either the machine side or utility side converters can be reduced by more elaborate bridge configurations.

Important special advantages of this system include:

- o Wide speed range.
- o High frequency torque pulsations.
- o Strong electrical damping.
- o Rapid reclosure after a fault.

Potential disadvantages of this system are:

- o Low frequency torque pulsations near synchronous speed.
- o High harmonic distortion.

Doubly Fed Induction Generator with DC Current Link Rectifier and Inverter

Another type of system which bears a great similarity to the synchronous generator scheme is the doubly fed induction generator. The system again uses a rectifier-inverter with a DC current link wherein the machine side converter is connected to three phase rotor windings by means of slip rings. Current flow is in 120 degree blocks at slip frequency on the AC side of the rotor connected converter and 60 Hz on the AC side of the stator connected converter. In principle, operation either above or below synchronous speed is possible. Synchronous speed in this case is defined as the point at which the rotor rotates synchronously with respect to the stator rotating MMF when the slip rings are shorted. When the machine generates below synchronous speed, power is supplied to the utility from the stator windings. However, power must be supplied to the rotor windings of the machine through the slip rings. The power required is essentially proportional to the difference between rotor speed and rotor synchronous speed (slip frequency) times rated power. Hence, the rectifier-inverter need only be rated for a fraction of rated power (slip power). In this mode of operation the rotor side converter operates as a variable frequency inverter. Conversely, when the machine generates power above synchronous speed, power is also extracted from the rotor via the slip rings. Again the converters need have a rating equal only to slip power. The rotor side converter operates in this case as a rectifier.

Among the particular advantages of this system are:

- o Converter ratings based on slip power.
- o Control response.
- o Harmonics.
- o VAR control.

This system has several particular drawbacks including:

- o Restricted speed range.
- o Torque pulsations.
- o Slip rings.
- o Lagging power factor.

Doubly Fed Induction Generator with DC Voltage Link Rectifier and Inverter

Whereas DC current link converter configurations obtain commutation volt-amperes from the connected supply, DC voltage link systems typically (but not inevitably) rely on commutation energy from special purpose capacitor circuits or by means of self commutating switches (transistors or gate turn on devices (GTO)). Such converters are inherently more expensive than DC current link converters. However, costs of such converters are decreasing rapidly with the development of new high power transistors and switches. If the desired speed range is small the

rotor connected converters need only handle a small fraction of rated power and the possibility of using a DC voltage link may be practical. Such a voltage link configuration has a rotor connected converter which operates in forced commutation while the stator connected converter commutates naturally. Other arrangements are possible in which the stator side converter (or both) are force commutated.

In general, forced commutated converters can be operated in either of two modes. In the six step mode the converter switches are triggered at the lowest possible rate to ensure a desired output frequency. In this case, the converter AC side line voltage assumes a quasi-rectangular wave shape which forms the dual of the DC link converter. Harmonics voltages of 5, 7, 11, 13, etc., times the fundamental are produced which in turn, induce currents of these frequencies in the corresponding AC current. In the pulse-width-modulated (PWM) mode, the switching frequency is modulated to eliminate undesirable harmonics. The switching frequency is sufficiently high that harmonic torques of concern in a wind turbine generator application are effectively eliminated. The presence of harmonics plus the large DC filter requirements of the six step mode suggests that PWM operation would be the preferred triggering scheme in this application.

Special advantages of a voltage link system are:

- o Smooth transition through synchronous speed.
- o High frequency torque pulsations only.
- o Smaller per unit rating than equivalent DC current link system.
- o VAR control.

Important disadvantages of this system are:

- o Cost.
- o Complexity.

Doubly Fed Induction Generator and Cycloconverter

An alternative to DC current or voltage link systems is the cycloconverter which is a device which transforms line frequency power to adjustable frequency power without an intermediate DC link. Numerous cycloconverter configurations have been proposed but the 36 thyristor arrangement is most widely used. This type of converter operates essentially as a voltage source. The cycloconverter is effectively a sampling type of converter where the input frequency is fixed and the sampling frequency changes with output frequency. In order to construct an output waveform, samples are taken from the three phase input. With proper modulation of the cycloconverter the current is nearly sinusoidal with superimposed harmonics related line frequency and to the switching frequency of the cycloconverter bridges. Because of the limits imposed by the sampling theorem, the output becomes progressively distorted as the output frequency is increased with about 1/2 the input frequency being the maximum obtainable with a 36 thyristor configuration.

The most pertinent special advantages of the cycloconverter fed, doubly fed induction generator scheme appear to be:

- o Power factor control.
- o Smooth transition through synchronous speed.

Several important drawbacks exist for this scheme which restrict somewhat its usefulness. They are:

- o Torque pulsations.
- o Harmonic structure of the injected line currents.
- o Behavior during single phase fault.

Cycloconverters can also potentially replace the dual converter bridge of a synchronous generator system. However, because the ratio of input to output frequency is restricted such an application would imply that the frequency of the generator would have to be kept relatively low (below 15 Hz) or relatively high (above 360 Hz) to provide for low harmonic distortion. Operation at such low or high frequencies would probably seriously restrict the design of the synchronous generator. Also, since full rated power would now pass through the cycloconverter, severe filtering problems could occur. Finally, serious power factor correction problems would arise, particularly for the low frequency option in which commutating VARs are required from the utility side to provide commutation energy for the cycloconverter.

DYNAMIC INTERACTION WITH THE UTILITY SYSTEM

The dynamic interaction of wind turbines and electric utility systems has been the attention of a number of studies. These studies have largely concentrated on wind turbine-generator systems which utilize synchronous generators [2]. A result of those studies was the observation of significant dynamic interaction within the turbine-generator system and between the wind turbine-generator system and the electric utility system. The internal oscillation is the so called first torsional mode which is highly oscillatory and lightly damped. If a synchronous generator is used as the electrical converter, these variations are faithfully reproduced thus producing a highly variable output power. In general, damping is provided through blade pitch control.

As interest has accelerated in variable speed generating technology, the properties of these systems have been examined more closely [3, 4]. In order to distinguish between variable speed generators (asynchronous) and synchronous operation two significant points should be made. In synchronous operation the torsional compliance between the electric generator and the utility system is low. As a result wind turbine-generator drive train swings against the utility. For variable speed systems (except for low speed slip induction generators), the compliance between the generator and the utility is high relative to the turbine-generator and drive train causing the generator to swing against the turbine. Hence, synchronous systems use blade pitch

control most effectively while variable speed systems use electric torque control to regulate torsional oscillation. Clearly, the dynamic properties are quite different.

Variable speed wind turbines also permit programmed variations of turbine speed as a function of wind speed, power level, or other process variables. This additional degree of freedom can have important benefits, such as higher turbine efficiency or reduced structural loads.

Most of the benefits of variable speed can be achieved with a relatively small speed range (20-30% of nominal speed). A small speed variation is also desirable to limit rotor exposure to natural frequencies. If slow turbine blade angle control is superimposed on fast generator torque control, the speed range required for input energy variations can be reduced significantly.

Dynamic interactions between wind turbine and utility system can largely be eliminated by variable speed. Within the constraints of rotor inertia and speed range, the generator can deliver constant energy even though the turbine is operating in a variable energy medium.

CONTROL SYSTEM REQUIREMENTS

The fundamental difficulty with control of wind turbines is the variation of input energy caused by changes in wind speed. In present designs of wind turbines, the variation in input energy causes changes in shaft torque because speed is held constant for synchronous generator operation. The drive train must be designed for the resulting torque excursions, both the steady state levels and the variations which can excite torsional resonances. There is little torsional compliance between present wind turbines and power systems.

The successful control of any system depends upon several key items. These include:

- o Specification of the input to which the system must respond.
- o Specification of the desired transient and steady-state response.
- o Some degree of modeling of the plant to be controlled, including sensors for measurement of output responses and control actuators for modification of the system input.

The control problems associated with variable speed wind turbines are much the same as those associated with fixed speed machines. The major difference being in the physical conversion process and perhaps the choice of control variables. Of course there is flexibility in what can be achieved with a variable speed system which is not present in fixed speed systems. The input specifications are roughly the same; that is, the turbine is to extract some measure of power from a widely varying source, the wind. The output specification is the delivery of power to an electric utility system at constant voltage and frequency and at as constant a power level as is practical. The problem of control of both mechanical

and electrical systems to produce smooth power from a sometimes rapidly varying wind source is both difficult and formidable whether fixed or variable speed is chosen. Both the fixed and variable speed systems require speed and/or torque control systems. A fixed speed system requires fixing blade rotation at some reference speed in the face of sometimes strong disturbances. A variable speed controller will probably require maneuvering the speed of the wind turbine to a point of maximum power capture during normal wind capture conditions and to some specified power setting during a power limit mode.

Several problems exist with current horizontal axis wind turbine systems that can be overcome by asynchronous operations:

1) Fixed-speed turbine efficiencies can be optimized through gearing selections for only one wind velocity. Net power capture is therefore less than could be achieved at wind speeds other than the optimal design speed.

2) A complex rotor-blade pitch-angle control servomechanism is required to limit power flow at average wind velocities above rated. This mechanism acts to limit mechanical wind torque by reducing turbine efficiency.

3) The mechanical shaft system is prone to very lightly damped oscillations for average wind velocities below rated. This behavior is due to the large rotor blade inertia, quill shaft compliance, and large step up gearing to the high speed generator shaft. These oscillations produce undesired stresses on the shaft components and make resynchronization of the generator after fault clearance difficult.

4) With turbine speed fixed, fluctuations in wind velocity produce corresponding mechanical torque fluctuations which pass essentially unattenuated into electrical power flow producing an undesirably large variance in electrical power.

A variable speed control system capable of fast control of generator torque can be used to adjust turbine efficiency, absorb wind gusting energy, and provide damping for shaft oscillations thus alleviating some of the difficulties encountered with fixed speed systems. Variable speed systems are of course, not without potential problems of their own.

The key control features for variable speed wind turbines are fast, electrical torque control at the generator and slow, mechanical speed control at the turbine. The programmed variations of turbine speed in response to other process variables can be introduced as changes to the turbine speed setpoint or the generator torque setpoint.

Turbine-Generator Control

In order to discuss specific trade-offs in control system design between fixed and variable speed systems, consider Figure 2. This diagram depicts a somewhat simplistic but yet generic wind turbine together with its various inputs and outputs including wind velocity, the blade pitch angle, and the rotational speed. Functionally, the aeroturbine combines these quantities to produce mechanical torque. The electrical torque produced by the electrical conversion process along with the utility

tie and the mechanical shaft torque are driven to some particular value in steady state. If a mismatch occurs, the deviation is used through the mechanical dynamics (including shaft compliances, gear-box, and inertias) to accelerate or de-accelerate the machine speed. Note the implicit feedback control loop. In a fixed speed system, the blade pitch angle is adjusted so that the difference between mechanical and electrical torque is a constant and hence the speed is constant.

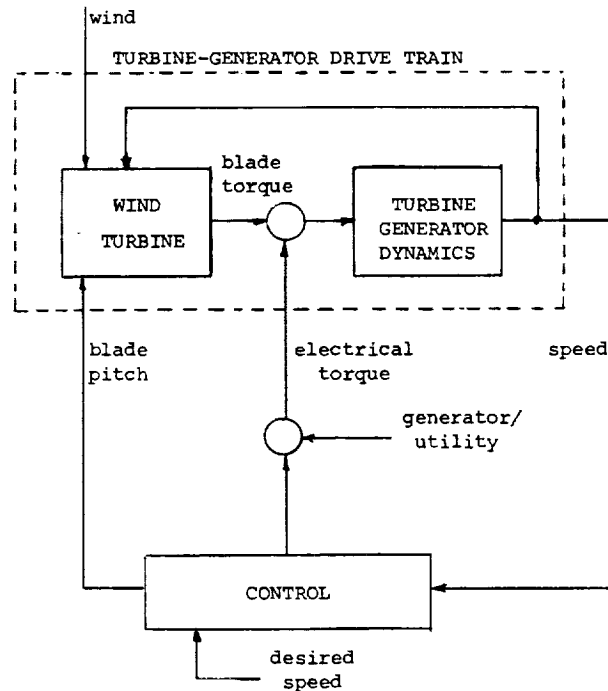


Figure 2. Wind Turbine-Generator System

Blade pitch and electrical torque are regarded as controllable inputs and wind speed as uncontrollable input. In a fixed speed synchronous system, the electrical torque is controllable through the exciter of a synchronous machine and not at all with an induction machine. Typically the exciter of a synchronous machine is used to control VAR flow, power factor, or for the regulation of terminal voltage.

In a real sense, blade pitch and electrical torque are equivalent speed regulating mechanisms excepting that one is electrical and one is mechanical. In all cases speed is shaped through the mechanical dynamics.

In a fixed speed system the desired speed is that speed which produces a 60 Hz electrical waveform. In a variable speed system, desired speed will probably depend on some filtered version of the wind speed. Figure 2 shows control through both the electrical torque and the blade pitch angle. Control through manipulation of electrical torque is more achievable in a variable speed system because in introducing the isolation between grid and machine, additional electrical control is available. One of the values of the variable speed generating options is this additional degree of freedom of effective control.

In variable speed systems, it is interesting to note that power can be spilled by either increasing the speed of the machine thus allowing the spilled energy to go into rotational energy, or by decreasing the machine speed to a more (but appropriate) inefficient operating point thus requiring more wind for the same output power. Either scheme will work for regulating power. Overspeed control would be preferable because the stored energy could be re-captured. However, the degree of overspeed will be determined through structural requirements. Clearly, there are trade-offs between turbine design, blade control, and electrical control that needs examination.

System Control Strategy

Wind turbine system control requirements should be based on the highest credible penetration of machines. It is well to remember that utility system needs are often neglected when new energy technologies are developed [5]. Essential system requirements of variable speed wind turbines are:

- o Proportional control of line frequency as a function of load. This is necessary so that generation can be adjusted in response to changes in load and that load can be shared with other sources in a controlled manner. Frequency control cannot be accomplished by turbine speed control because line frequency is no longer dependent on turbine speed. Converter equipment used in the variable speed system cannot depend on line frequency for commutation.
- o Control of line voltage. This is necessary to provide voltage support to the power system. Var generation as well as var absorption should be possible.

While the feasibility and philosophy of variable speed control system design have been examined, there are additional problems that may occur. Because of recent trends in wind turbine mechanical design to "flexible" systems (flexible blades, teetering hubs, soft shafts, etc.) many modes exist in the structural and torsional design. These are cause for concern and the flexible design policy needs to be re-examined in light of the possibility of exciting these modes with variable speed operation. Mode avoidance can be accomplished to some extent through control policy but would not be preferable to designing the troublesome mechanical modes out by rigid blade and tower construction if possible.

In addition, electrical speed control is favored over mechanical control because of its simplicity. There are no rotating couplings to leak or pneumatic actuators to fail. It remains to be seen what

generator torque requirements are necessary to accomplish the control. Finally, the specification of the input and output are an issue. The control system designs should be flexible enough to follow a reasonable variation in the wind while the output should have the capacity for arbitrary smoothing (at the expense of loss of wind capture).

CONCLUSIONS

An examination of variable speed electric generating systems for wind energy has been provided. The three key elements discussed include variable speed options, dynamics of variable speed systems, and control. The merits of the variable speed system include high wind turbine collection efficiency and superior dynamic properties with the addition of proper controls. Inefficiency in the variable generator can be minimized through careful design.

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