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# ANALYSIS METHODS FOR WIND TURBINE CONTROL AND ELECTRICAL SYSTEM DYNAMICS

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ABSTRACT

The integration of new energy technologies into electric power systems requires methods which recognize the full range of dynamic events in both the new generating unit and the power system. Since new energy technologies are initially perceived as small contributors to large systems, little attention is generally paid to system integration, i.e. dynamic events in the power system are ignored. As a result, most new energy sources are only capable of base-load operation, i.e. they have no load following or cycling capability. Wind turbines are no exception. Greater awareness of this implicit (and often unnecessary) limitation is needed. Analysis methods are recommended which include very low penetration (infinite bus) as well as very high penetration (stand-alone) scenarios.

## INTRODUCTION

Electric power systems are the largest readily available market for new energy sources. Interconnection with utility power systems is generally a prerequisite for economic use. The technical issues of interconnection can be viewed in different ways. For the purposes of this paper the two extreme views will be called 'connection' and 'integration'. Connecting a new power source to an electric power system is analogous to connecting an appliance to an outlet. If the appliance is compatible with the voltage and frequency present at the outlet and if the current drawn does not exceed the rating of the wires connecting the outlet, interconnection is successful. This view is the one most likely taken when small sources are connected to large systems. It is the classic low penetration perspective. Implicit in this perspective is the assumption that the power system is an immense, static reservoir of energy, devoid of any dynamics.

Integrating a new power source into an electric power system is a very different activity. A typical scenario which requires integration rather than connection is an isolated 5 MW diesel power plant to which 2 MW of wind turbines are added. Such a plant may supply power to an island, with loads varying between 3 MW during the day and 1.5 MW during the night. Integration is necessary whenever the power system is finite with respect to the new source, i.e. it is inherently associated with high penetration.

This paper examines analysis methods used for wind turbine interconnection studies to determine why the connection viewpoint has generally been taken, and what the consequences have been. It is shown that this viewpoint has not only prevailed in wind turbines but in many other new energy technologies as well.

The material is organized in six parts:

- Part 1 is a review of the relevant features of power system controls and dynamics
- Part 2 discusses the relevant characteristics of wind turbines
- Part 3 defines requirements for integration of new energy sources
- Part 4 identifies the reasons why new energy sources are often connected rather than integrated
- Part 5 discusses the course taken in interconnecting wind power
- Part 6 contains conclusions and recommendations.

## 1. CHARACTERISTICS OF ELECTRIC POWER SYSTEMS

Let us recall the characteristics of power systems that are relevant to integration of new power sources:

- Equilibrium of Generation and Load

  System frequency only remains at the nominal value as long as generation and load are equal. Load is not controlled by the utility but by its customers. If load exceeds generation, system frequency and generator speeds will decrease because kinetic energy is drawn from the rotating inertias to make up the generation deficiency.

- Primary (Turbine) Control

  Individual generator speed controllers (governors) respond to the decrease in speed and admit more steam or water to their respective turbines. This is the initial (primary) response of the system to a disturbance. It takes place at each machine, which has an active speed controller. The speed controllers have proportional characteristics, i.e. every new equilibrium between generation and load is associated with a new system frequency. The use of proportional speed controllers with the same regulation (droop) from zero to rated load permits sharing of load in proportion with generator capabilities.

- Secondary (System) Controls

  Another control function is needed to return system frequency to the desired value. Load frequency control is a system function with slow integral characteristics. It operates by remotely raising the speed setpoints of participating generators. In addition to load frequency control, secondary control exercised at the system level is also responsible for economic dispatch and unit commitment. Economic dispatch gives the source with the lowest incremental cost preference to supply the next load increment. Unit commitment predetermines a reliable and economic generation mix for future, predicted loads.

- Load Cycle and Spinning Reserve

  Within a 24 hour period the minimum load in an electric utility system is typically 40 to 70% of the maximum level. The secondary (system) control functions which establish and maintain economic and reliable use of system resources must therefore change generation mix and generation levels daily, both in a predictive and an adaptive manner. The dispatch of system resources exercised at the system control level must also provide a suitable reserve of spinning, on-line generation for contingencies, i.e. there must be generators which operate below rated power, ready to increase their generation when a sudden generation deficiency occurs. The spinning reserve must be distributed to a sufficient number of generating units so that the aggregate speed of response of generating units is fast enough to arrest a frequency decay. It should be noted that most large steam turbines have rates of response of only 1 to 2% of rating per minute due to large thermal time constants of turbines and steam generators.

## 2. PROCESS CHARACTERISTICS OF WIND TURBINES

There are five peculiarities which characterize wind turbines from the viewpoint of system integration:

- Non-Steady Energy Source

  The bandwidth of input energy fluctuations ranges from nearly zero to about 1 Hz. This causes output fluctuations reflecting both the input spectrum and drive train torsional modes excited by the non-steady energy input.

- High Turbine Inertia and Low Torsional Stiffness Between Turbine and Generator

  This causes low frequency torsional modes below 1 Hz and decouples turbine and generator during disturbances.

- Speed/Torque Characteristics

  This can vary from constant speed variable torque for a synchronous generator to variable speed constant torque for a variable speed generator. Induction generators occupy an intermediate position between these two extremes.

- Voltage/Reactive Power Characteristics

  Synchronous generators provide waveform, phase balance, and variable reactive power for voltage control. Induction generators provide waveform and phase balance, but absorb reactive power and cannot provide voltage control. Frequency converters used with variable speed wind turbines may neither provide good waveform and phase balance nor voltage control and may actually depend on the presence of a strong power system for commutation of their thyristors.

- Turbine Control

  If the turbine has variable pitch blades, energy capture can be controlled. The choice of the controlled variable (torque, power or speed), the type of control (proportional or integral or both), and the gain of the control loops determine how the turbine operates in an interconnected system.

## 3. REQUIREMENTS FOR SYSTEM INTEGRATION

From the description of power system characteristics we can draw two conclusions:

- New power sources should be able to follow changes in load. Changes in generation due to load following must be associated with changes in frequency. Load following capability should be dispersed throughout the system to achieve an adequate rate of response. Dispersal is also desirable so that parts of a system can survive as electrical islands after a system breakup.

- New power sources should be able to operate at different levels of generation in response to commands from a system dispatch center. Whether a particular generating unit will be used for base-load or cycling duty depends on the resource mix of the particular system. Since different systems have different resource mixes, a particular technology may be used for base-load in one system and for cycling in another system. Any inherent restrictions a particular generation process imposes on operating flexibility should be built into the utility dispatch strategy, not implemented in the control design of generating units.

## 4. TYPICAL DEVELOPMENT OF A NEW ENERGY TECHNOLOGY

The need for analyzing interconnection issues typically arises at a time when the new process itself is not fully understood and the associated equipment is under development, i.e. when analytical resources are preoccupied with process and equipment issues. Since the process is new, a low penetration scenario is always envisioned at the outset [1]. It is not surprising that the interconnection viewpoint taken at this time is that of connection, not integration. Unfortunately, this is also the time at which decisions must be made about control of the process. In this manner, the operating characteristics of new utility power sources are often established before any thought has been given to system integration. The result of this are sources only suitable for base-load operation. Examples other than wind are steam plants with once-through steam generators (supercritical) and steam plants with nuclear reactors [1]. It is interesting to note that in both of the latter cases process control was not changed when the original premise of low penetration was no longer valid.

Two other factors may aggravate this systematic flaw in our method for developing new energy technologies. The first is the ever necessary economic justification. Proponents of new technologies obviously assume base-load duty for their economic calculations because it minimizes the impact of fixed costs. It may very well be that after a long process of economic justification, organizations find it intolerable to contemplate control systems which would allow a new source to do anything but maximize energy output. They may feel that any other mode of operation would invalidate their economic justification. The second factor is the recently enacted PURPA Law. Independent power producers selling power to utilities want to maximize revenue and are only interested in contributing to the base-load component of the utility load. Manufacturers producing equipment for sale to independent power producers will find little demand for features necessary for system integration.

## 5. DEVELOPMENT OF WIND POWER

The phenomena just described have strongly influenced wind power development. Preoccupation with process requirements and low penetration scenarios has led to many wind turbine designs without load following or cycling capability. It may be argued that contrary to steam plants with supercritical and nuclear steam generators wind will always be a low penetration technology. In the author's opinion, such reasoning is flawed because it overlooks that wind turbines may be very competitive in small isolated systems with high fuel costs.

The following three examples illustrate how these thoughts have influenced wind turbine analysis and the resulting wind turbine control and equipment design.

- o Damping of Torsional Modes

  A common method for representing the electric utility system in wind turbine analysis is the so-called infinite bus. An infinite bus is dynamically equivalent to a generator with infinitely large rotating inertia and infinitely small electrical resistance, i.e. frequency and voltage of the utility tie are always constant. This is low penetration in its purest form, the utility system is always at steady state.

  If torsional oscillations of wind turbine drive trains are examined with a simulation system that represents the utility system with an infinite bus, it is found that the best place to introduce damping of the predominant torsional mode is at the turbine. The mode shape reveals that the torsional amplitude is much higher at the turbine than at the generator. This is caused by high system inertia and low torsional stiffness between turbine and generator. This type of analysis had led to damping by modulating blade angle. It has been shown [3] that the mode shape of the dominant mechanical mode changes with penetration. If wind turbines dominate system inertia, as may be the case in small isolated systems, the predominant torsional motion shifts from the turbines to the generators. The effectiveness of damping by blade angle movement decreases. This relationship between torsional damping and penetration is not recognized when electrical system representation is based on an infinite bus.

- o Turbine control

  When wind turbine controls are analyzed in a simulation environment which does not allow frequency variations, primary speed control of individual generators with proportional controllers and secondary reference adjustment with integral controllers makes very little sense. In such an environment the obvious method for controlling a variable pitch wind turbine is to adjust blade angle to maintain constant power. This method provides the necessary torque control and maximizes energy capture. This is what most wind turbine designers have done. The result is a resource suitable only for base-load and low penetration.

- Variable Speed Wind Turbines

  In the last two years there has been much interest in variable speed, constant frequency wind turbine generators. This type of wind turbine uses frequency converters to change variable frequency to constant frequency alternating current. Frequency converters are difficult to apply in high penetration scenarios because they may need frequency and voltage references and they may distort waveshapes. A designer of such a system has to recognize that the wind turbine must be able to follow load with changes in generator frequency in order to participate in primary control. There is a simple test which determines whether a variable speed wind turbine with frequency converters can be integrated into a power system. If it can function as a stand-alone source for a variable load, it can be integrated. The validity of this test is not limited to variable speed wind turbines. It can be applied to any new energy technology. It is easy to see why this test is valid. The historical basis of utility systems is interconnection of autonomous, stand-alone sources. Interconnection improves economy and reliability, but is not a prerequisite for operation. A source capable of stand-alone operation in a variable load system has all the attributes necessary for system integration.

## 6. CONCLUSIONS AND RECOMMENDATIONS

What conclusions can one draw after surveying power system integration of new technologies in general and of wind turbines in particular?

The first conclusion would have to be that any claims about successful integration of wind turbines should be very modest. Connection would be a more appropriate term. Our analysis methods and our control design have largely ignored dynamics inherent in the power system. In most actual installations the implicit assumption of low penetration has fortunately been justified. The second conclusion is that the same situation exists in almost all other new energy technologies. It exists in nuclear steam plants, supercritical steam plants and there are signs that it may happen in photo-voltaic power sources. The particular scientific and engineering community always considers its technology to be the star of the show and assumes without examination that other technologies can play supporting roles as needed [2]. This somewhat parochial view is one of the main causes of a structural flaw in our method of organizing energy development efforts.

Recommendations range from the necessary minimum goal of increased awareness in the wind turbine community to the desirable maximum goal of better analysis tools and improved control design.

Increased awareness is needed because there are several potential applications in the United States where the present analysis methods are unsuitable because the implicit assumption of low penetration is no longer valid. One example are the Hawaiian islands other than Oahu. These islands have excellent wind resources and small electrical systems (5-100 MW).

A recent study of controls for variable pitch wind turbines for NASA-Lewis includes analysis methods and control designs suitable for high penetration scenarios [3]. The basic difference between the traditional and the recommended analysis method is that with the latter the candidate system must function not only in an infinite bus but also in a stand-alone environment. Stand-alone simulation is a necessary complement to infinite bus simulation. Both are abstractions, and both have the advantage of computational simplicity. The actual applications lie between these two extremes.

## REFERENCES

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