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A REVIEW OF UTILITY ISSUES FOR THE INTEGRATION OF WIND ELECTRIC GENERATION*

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ABSTRACT

A review of issues and concerns of the electric utility industry for the integration of wind electric generation is offered. The issues have been categorized in three major areas: planning, operations, and dynamic interaction. Representative studies have been chosen for each area to illustrate problems and to alleviate some concerns. The emphasis of this paper is on individual large wind turbines (WTs) and WT arrays for deployment at the bulk level in a utility system.

INTRODUCTION

The primary issues and concerns regarding the integration of wind electric generation into utility systems can be classified into three major categories: planning, operations, and dynamic interaction. Planning involves an assessment of the feasibility of including wind energy conversion systems (WECS) in the future generation mix of the utility. Operational issues focus on the dispatch of generating facilities with primary concern on the impact of the variable output power of WT arrays on the utility system, including the real-time control and the economic dispatch of both the conventional and the WT units. Dynamic interaction is concerned with the oscillations of power, voltage, and frequency between the WT and the other generating units in the utility system.

The activities within planning, operations, and dynamics span a wide time frame ranging from seconds to years. Dynamic interaction is confined to time frames of milliseconds to minutes while operational issues cover the dispatch of WT arrays and conventional generation

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units spanning time from seconds to days. Generation and transmission planning, on the other hand, is normally performed for a period that is years in the future.

The purpose of this paper is to focus on the critical utility issues within planning, operation, and dynamics as they relate to WECS integration. This document can serve as a guide to understanding utility system concerns, not solving them; and hence it should be useful to utilities, WT designers, and other organizations that are interested in wind electric generation. Representative studies, either completed or ongoing, have been chosen to illustrate potential or observed problem areas as well as indicate how some of the problems have been resolved. The emphasis is on individual machines or arrays that are connected to the bulk transmission network, a likely utility application. Those studies that are associated with the mechanical properties of WECS, WT design and small customer-owned WECS are not considered.

PLANNING

The purview of electric utility system planning includes the totality of the system: generation, transmission and distribution. This discussion focuses on large wind electric systems that are deployed as single units or arrays connected to the bulk transmission system, hence distribution planning is omitted. Distribution planning is a key issue for non-bulk intertie.

Transmission

The primary issues facing the integration of WT systems are within the generation planning framework, however, transmission planning does require some discussion. In transmission planning, capacity requirements and overall system stability are dominant considerations. From the perspective of the transmission system, electric production from present designs of WTs is no different from production from conventional generation, hence present transmission design practice is adequate. The transmission capacity requirements are determined by the relative geographical location of the generation and the load and to the total power transport requirements. Two studies [1,2] have considered transmission capacity needs and have shown those needs fall within normal requirements of transmission design. Since, the transmission system is also vital to overall system stability and is critical when generators oscillate against one another, two studies [1,2] have considered these needs and have found no unique transmission requirements to accommodate a WT array. In general, present WT designs have very little, if any, unique influence on transmission plans thus relegating most efforts to engineering design solutions.

Generation

Electric utility systems are designed to operate at minimum cost with a prescribed level of reliability. In order to meet these goals, a generation expansion plan for capacity additions is devised to meet the next increment in load growth by minimizing the total cost, i.e., the capital, fuel, operating, and maintenance costs. The planning horizon is a multi-year evaluation, typically 30 years in length. Since many years are spanned in the evaluation, "present worth" or discount of future costs is used to determine the total costs. Typically, several generation expansion plans will be tested to determine the most viable option while recognizing that the least cost choice must satisfy the reliability requirements.

The key requirement in the expansion plan is the least total cost over the planning period. Therefore, the capital cost of various generating unit types must be weighted against the costs to operate these units. The "trade-off" is typically determined by assessing the cost of production by dispatching a given generation expansion plan against an hourly load profile over the planning period. An iterative search is performed by varying the unit types while meeting the load requirements on an hourly basis.

Simultaneously, the reliability requirements are assessed. Since all generating units exhibit some unplanned outage time, the need exists to plan for generation in excess of load to cover the contingency for loss of generation. The planning criteria is the commonly used index for generation system reliability, the loss of load probability (LOLP) which is the probability that load exceeds the available generation. LOLP is used to indicate the expected number of events in which load is greater than generation.

There have been many studies examining the impact of wind energy on electric generation planning, far too many to enumerate here. In general, these studies [3-6] have focused on modifying present generation expansion assessment methods to include wind electric systems. The key to establishing the value of wind electric generation to electric utility systems is the identification of factors such as timing of energy production, correlation between energy production and load, etc., which affect total system performance. The impact of these factors is influenced by both the assessment methodology and the economic assumptions. A review [7] of most of the methods has been published and is recommended reading in this area. Additional work remains for improving the effectiveness of conventional models, however, new techniques for assessing the value of non-conventional technologies such as wind is needed.

A planning manual [8] for evaluating the worth of WECS to utility systems has been developed as an aid to utility managers, planners, engineers, and consultants. The approach is consistent with or is an extension of present utility generation planning methods with particular emphasis on how wind can be considered as a generation source. A two-step approach is used in the manual. The first step is a preliminary evaluation of WECS value requiring many simplifications with the result strongly dependent upon the average annual wind velocity in the general service area of the utility. The first step is intended to inform the user if a detailed evaluation is warranted. The second step is a detailed evaluation including all the conditions planners have found necessary for successful generation planning and the removal of the simplifying assumptions used in the preliminary evaluation.

Uncertainty in the planning of utility systems with WECS has focused on cost and performance of wind turbines. Although a number of experimental machines have been deployed in the field, in general, data from non-research activities is needed. One study [9] suggests that most cost data to date has failed to account for all the WT installation, land, interconnections, transformers, protection equipment, project maintenance, O&M, etc. Most planning studies have used non-site specific data and have resulted in capacity factors for machines larger than those observed in practice [5,10]. Better data on cost and performance of WECS will become available as utilities gain installation and operating experience.

A good overview of the economics and development status of WTs is provided in a DOE/NASA report [11]. Wind turbines were shown to be more economical when arranged in clusters of 25 or more units. The major difference between the 25-unit cluster and a single unit is labor, operation, and maintenance costs. Also, the availability of a WT array for energy production was estimated higher than that of a single unit.

One of the first steps in evaluating the potential of wind energy is to determine the wind characteristics of potential sites. Hourly average wind data at potential sites is needed, however, it is often not available. This is a major difficulty in performing economic dispatch planning assessments. Several sources for wind data do exist, including monthly average wind power for 101 sites [12]. Information on wind is also available from Battelle Pacific Northwest Laboratory reports [13,14].

DYNAMIC INTERACTIONS

An electrical power system is in a state of constant dynamic motion resulting from load changes, changes in production level at various power plants, and network switching. In general, these perturbations cause excursions of power, frequency, and voltage at the system's natural frequencies of oscillation which are usually sufficiently damped to prevent a sustained system oscillation or one that grows with time. Systems exhibiting these properties are said to be stable. The addition of WTs could over-excite normal, highly damped modes or excite new modes resulting in utility system stability problems. It is important to distinguish between system and WT instabilities since the former could severely restrict the use of WTs by utilities.

Fluctuations in wind velocity result in variations in WT output which could cause severe system power swings, frequency variations, and/or system instability. The severity of the problem is determined from a combination of generation mix and type, load profile, and overall operational procedures. Dynamic and transient analyses on the impact of WT variations on utility systems have been performed in several studies [15-18]. An early GE study concluded that WECS were marginally stable with moderate wind gusts and exhibited unacceptable voltage and power angle oscillations with severe gusts [15]. The study recommended stability improvement measures which were considered in later design studies for advanced WTs. In general, utility system stability has not been threatened by WTs.

The dynamic and stability properties of large modern wind turbine generators connected to power systems has been studied by Hinrichsen and Nolan [16,17]. It was shown that the dynamics of WTs are dominated by the torsional characteristics of the drive train. WTs have a relatively soft shaft that has a decoupling effect on electrically and mechanically produced transients. The unusual torsional system characteristics of wind turbines provide the ability to synchronize a WT through large phase and speed mismatches, however, its transient stability properties under automatic circuit breaker reclosing is poor. No adverse interactions were found for groups of WT units synchronized together. The dynamic behavior of multiple machines was found to be similar to that of a single machine.

The two most severe electrical disturbances for the WTs are short circuits in the vicinity of the generator terminal and complete loss of load followed by subsequent restoration of load [17]. Both disturbances result in large electrical transients.

During a loss of load, the generator rotor moves quickly away from the synchronous reference position. However, the turbine which is coupled to the generator with a soft shaft continues to operate close to synchronous speed. If resynchronization is attempted under these conditions, large electrical transients result. Since the mechanical stiffness is much lower than the electrical stiffness, electrical transients result in large forces on the generator windings. Studies at Purdue University found that arbitrary reclosing should not be employed [18]. A modified WT hub speed control is suggested for reclosing and reloading the machine. Special protection practices must be developed to prevent mechanical damage to the WT generator. The development of protection guidelines is the objective of several present studies.

The dynamic impacts of large penetrations of wind generation on the Hawaiian Electric Company (HECO) utility system was assessed by Zaininger and Bell [2]. No stability problems resulted from adding 80 MW of wind generation capacity to the HECO system although the WT array generator equivalent was found to be very active after a disturbance due to the very small shaft inertia compared to that of conventional generators.

WT dynamic impacts are a subject of continued investigation. The Electric Power Research Institute is funding a research effort to develop a methodology for determining the dynamic impacts of wind turbines on utility systems.

OPERATIONS

Electric utility operations cover a wide range of functions, including operations planning, economic dispatch, frequency control and load following. These functions are affected by a combination of level of penetration as a percent of instantaneous load and when the WT production occurs. A number of measures for penetration have been employed such as percent of peak load, percent of dispatched generation, percent of peak capacity, etc., however, most of these measures are ineffective in capturing the essential factors affecting power system operations. At modest levels of penetration relative to system load, the impact of WTs has been small [19], however, the type of generation, small diesels, is a significant fact. As penetration levels are increased, the variable nature of wind plant production could have significant impact on the operations of the utility system such as excessive ramping of generators and unacceptable frequency variations. Many of these impacts will tend to economically limit the practical penetration levels of wind generation for utility application.

Unit Commitment and Economic Dispatch

An important aspect of power system operations is pre-dispatch or unit commitment. This aspect of operations planning schedules production on a one to three day time horizon in anticipation of load level and reserve requirements. The power plants are then economically dispatched, typically on 10-30 minute basis. The affect of WTs on these two processes has not been fully investigated. One study [1] in progress is investigating the impacts on unit commitment.

The economic dispatch issue will be considered as utility data becomes available from sites where cycling of power plants might disrupt normal dispatch levels. The effect of wind generation penetration on total system operating costs is a combination of dispatch policy and unit sizes. For a specific generation mix there is a maximum penetration level of WTs that can be optimally accommodated. Beyond that maximum penetration level, the cost penalty is greatly increased by a departure from the optimal dispatch of the generation as imposed by the increased load following requirement.

Load Following and Frequency Control

The cyclic variations in load require the capability to cycle power plants such that a high quality of electricity is maintained, i.e., proper frequency and sufficient capacity. Thus, power plants must have sufficient response capability to follow load both in magnitude and rate of change. Typically, these needs are met by distribution of the system's instantaneous load carrying capability among several units. It is desirable to limit the number units for load following since the economic operation of the plants is compromised in this mode. Clearly, WTs could add to the load following requirements of the conventional plants.

A number of studies have shown that load following and frequency control requirements can increase for significant penetrations of wind plants on a utility system [2,5,20,21]. Penetration levels that are significant are correlated to the type and size of the generation mix and the wind resource. A primary application of wind power generation is expected to be large arrays of megawatt size WTs connected to the utility bulk transmission network. While large arrays are more economical than dispersed wind turbines, array output power variations due to weather fronts can cause excessive frequency excursions. To limit frequency and area control error deviations, one study has recommended that the rated WT array capacity should be limited to a few percent of the utility's system capacity [21]. In another study, it was found that minute-to-minute ramping and daily frequency excursion limits may require WT operating restrictions and/or increased spinning reserve [2].

The impact of intermittent generation on load following and spinning reserve requirements have been studied by several investigators [1,5,20,21]. One study [20] indicated that spinning reserve and load following requirements increased almost linearly with respect to penetration of intermittent generation for the utility that was examined. Increased spinning reserve requirements for significant penetrations levels have been suggested from other studies as well [1,5,21]. As spinning reserve and load following requirements increase, the economic benefits of wind electric generation per rated capacity decreases. This is due to the cost penalties associated with reductions in conventional generation unit efficiencies. All of these studies treat wind generation as negative load.

SUMMARY

A review of issues and concerns of the electric utility industry for the integration of wind electric generation has been performed. These issues have been classified as planning, dynamics, and operations. Selected studies in each of these areas have been discussed.

The discussion focuses on generation and transmission planning since the WT applications have been limited to bulk system intertie. A difficulty in performing planning studies for wind electric generation is the lack of utility acquired data on installation and operation costs from non-research oriented activities. Utility experience with WTs in the near future and improvements in wind forecasting methods will reduce these uncertainties.

Dynamic analysis of WT arrays interacting with utility systems and individual WT interaction have not revealed any serious problems. Studies in this area are continuing.

Operational impacts of WT arrays could be significant if penetration levels are not carefully coordinated with system response and dispatch requirements. The variable nature of wind could cause present spinning reserve and load following practices to be inadequate to meet traditional utility operating guidelines. Further research is required to identify critical parameters which are needed to establish the relationship between the dispatch, control, and operation of WTs and utility systems.

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