Operations of Electric Power Systems with High Penetration of Wind Power: Risks and Possible Solutions

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Abstract— **This paper provides an assessment of wind power effects on technical and economic performance of today's electric power systems. While a small penetration of wind power is unlikely to cause any qualitative changes, significant deployment of wind-generated power will require a major rethinking of generation dispatch and automatic generation control, in particular. We summarize technical risks, as well as the economic implications on total cost of providing power to customers. The discussion is presented for both traditional fully regulated utilities and for the portions of the electric power interconnection which are undergoing restructuring. The paper suggests that the ultimate benefit of wind power to the customers will depend to a large extent on how well today's operating practices are adjusted to make the most out of the available resources, including the intermittent wind power. Moreover, we suggest that an analysis should be done to determine the amount of wind power for a given system beyond which benefits are difficult to capture because of the necessary additional infrastructure cost.**

I. Introduction

Wind-generated power is currently viewed as a very promising energy resource with many desired characteristics, in particular it is thought of as being the ultimate clean power [3], [7]. Smaller scale wind power plants have already been built in many parts of the world. As the technology continues to improve, their average cost has become comparable with the cost of more conventional electric power plants. In this paper we assume that various predictions concerning potential large scale penetration of wind power are likely to happen and assess the operational risks associated with this process. We recognize that this risk assessment is more involved than when planning for controllable power plants and it requires, therefore, a more detailed knowledge of operating and planning practices. In particular, risks are dynamic and may vary significantly with both spatial and temporal characteristics of the electric power grid.

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In what follows we first consider the problem assuming current operating and planning practices. In the second part we suggest possible solutions to moving forward and for overcoming the perceived risks.

II. The Effect of Wind Power on Operations Planning

Small-scale wind power is typically intended to supply customers in the same geographical area. This is very different from the large-scale power plants which require power delivery across vast geographical areas to many customers. However, as the large-scale wind power is built, it is likely that large wind farms will be located in places far away from the end users. A large wind farm may have a similar rating as a typical large-scale power plant of today. While it may appear to be the same at first sight, its impact on required operating capacity and regulation reserves is qualitatively different. Moreover, its impact is very different in areas where wind blows in the winter from areas where wind blows in the summer because of different correlations between the load and wind cycles. There are several major uncertainties created by the presence of intermittent wind power that are critical at the operations planning stage.

- How much planning and operating generation capacity is needed to supply utility load according to the $(N-1)$ criteria ;
- How much regulation capacity is needed to compensate for wind-created uncertainties, in addition to the regulation needed to compensate for the uncertain load;
- How much additional transmission capacity is needed.

These questions cannot be answered accurately without careful statistical characterization of wind power. Much inefficiency and the associated operational and financial risk comes from not knowing locations and timing of building wind power plants, and from not knowing their operational characteristics. One must know at least what percentage will the wind power plant likely be generating power, as well as what is the most likely power shape as a function of time. Moreover, for regulation, it is needed to know the likely bounds on amplitude deviations around its mean time-varying power profile, as well as the rate of deviations. Today's planning practice does not require this type of information and it, therefore, falls short of integrating wind power effectively with the existing energy resources.

A. Implications on Electricity Tariffs

In order to assess these implications, we recall that in regulated industry costs associated with uncertainties of any kind are allocated according to the peak load of customers. This is done independently of their actual power profile and is not directly related to who is causing the uncertainties.

Implied in today's electricity tariffs is a strong assumption that load can be forecast quite accurately and that feed-forward unit commitment and economic dispatch could be done to balance the majority of anticipated demand by scheduling available generation in merit order [5]. Current operating practice is that relatively slow supply/demand imbalance, which is hard to forecast, is compensated by means of Automatic Generation Control (AGC) in a feedback automated manner. Recently the industry has revisited the performance criteria of AGC. In particular, the industry has moved from requirements to meet $A1$ and $A2$ performance criteria which set specifications on targeted deviations in area control error (ACE) during normal and emergency conditions, respectively, to somewhat relaxed $CPS1$ and $CPS2$ corresponding requirements [2]. Qualitatively speaking, there have been two major changes: (1) instead of requiring that tie-line flows be kept close to their intended schedules ($A1$), the industry requirement is on frequency deviations only, with somewhat free-flowing tie-line flows in between the control areas ($CPS1$); and, (2) instead of requiring tight control, such as ACE crossing zero every 10 minutes, the new frequency control standards are expressed in terms of average frequency deviations on annual basis, in order to avoid un-necessary wear-and-tear of AGC units. A close look into these changes of industry standards shows that the rationale for new standards revolves around the old assumptions that deviations around possible forecasts are statistically close aimed at zero mean noise [6]. Targeted industry efforts toward implementing the new standards in a seamless way with already existing AGC functionality have led to several very important designs [2].

The key operations planning question concerns the effects of technologies that do not lend themselves to the assumption that deviations in supply/demand imbalances are white noise around the supply/demeand forecast. There are several major technologies which are likely to contribute to a significant violation of this assumption, notably real-time demand pricing and intermittent generation.

B. Effects on Electricity Tariffs in Regulated Industry

High penetration of wind power is likely to require significant operating reserves around the peak load because of both load uncertainties and uncertainties in wind power. A risk-averse operator is likely to view wind power as a "negative" load. In much the same way as with other loads, the operator will look at its predictable component and schedule resources assuming that less other generation would be needed as a portion of the demand will be supplied by the portion of wind power which is within the reach of accurate forecast. Simple algebra shows that if the percentage of wind is large, and its correlation with forecast demand is not accounted for carefully, the net effect would be that the operator would perform joint optimization for energy and operating reserves, resulting in the need for huge amounts of operating reserve.

Moreover, depending on how predictable wind deviations are, there will be a definitive need for more regulating generation in order to compensate for hard-to-predict wind deviations. In other words, in addition to AGC reserves to compensate for hard-to-predict load deviations, the operator will have to plan for regulation reserves to compensate for fast hard-to-predict wind power deviations, as well. Assuming that wind power forecasts are quite accurate, there will still be a need to have stand by regulating power to compensate for now much larger spikes in net supply/demand deviations in power around the forecast supply/demand profile. Again, if the fast deviations in wind are large due to a shear volume of wind power, it will be necessary to have much more stand-by regulating generation in order to maintain frequency within the recommended industry standards. It is at this point that following the old regulation standards ($A1$, in particular) will be much more costly than following the newly proposed standard ($CPS1$, in particular).

It is essential that we assess these costs and their impact on customers' tariffs. A fairly straightforward approach would be to compare:

- Unit commitment and economic dispatch savings

brought about by the wind power component which is of a predictable power profile;
- Additional costs of AGC for accommodating hard-to-predict components of wind power.

It is essential to keep in mind that the main cost of AGC is due to out-of-merit unit commitment and economic dispatch, and to a much lesser extent due to the fuel cost of regulating plants [6]. This calls for a very careful assessment of potential operational savings due to wind power. Moreover, in order to reap the benefits of wind power unit commitment, economic dispatch and regulation must be revisited. The basic objective would be to optimize these tradeoffs without sacrificing system performance. State-of-the-art ideas for such optimization enhancements can be found in [1], [4], [2].

To conclude, the answers regarding the impact of intermittent power such as wind on long-term electricity customer tariffs very much depends on how the wind is managed as part of operations planning. One thing is for sure: The better the wind power forecasts are, the higher the benefits. This is fairly straightforward to document using potentially large out-of-merit AGC costs caused by poor forecast. These operating benefits need to be compared with the capital costs of various candidate generation and demand-side management technologies for managing long-term load growth. In addition to the energy and capital costs associated with serving electricity to customers, it has been suggested there exist hidden very long-term environmental costs of very large-scale wind penetration [7].

The net answer to total economic effects on electricity prices to customers will have to account for all of the above. The answer is definitely dependent on the time horizon over which the assessment is done.

C. Effects on Electricity Tariffs in the Industry Under Restructuring

The assessment of large scale wind power effects on electricity tariffs in the changing industry is much more involved. This is largely due to the overall design of today's electricity markets in which only energy is paid by those who use it; the uncertainties of any kind are managed and paid for in an asymmetric way by and large [4]. This is generally not a problem, unless uncertainties are major. In particular, in an industry with locational based marginal prices (LMPs), poor prediction/knowledge of relatively large deviations in wind power around the forecast could contribute significantly to the differences between a Day-Ahead Market (DAM) and Real-Time Market (RTM) prices. The real time prices are likely to exhibit large and frequent spikes caused by significant uncertain components in wind power generation.

Another major aspect of large wind power effects in the changing industry comes from having to manage power across the multi-control area interconnection, instead of by each control area only. The statements here are very sensitive to which industry standard is pursued in the restructured industry. At present, the inter control area/electricity markets issues are known as the seams problems, and await regulatory and technical solutions. While this is the case, we can expect large unaccounted for effects of wind across the interconnection on the export/import power flow patterns, and on the need to manage these.

It is practically impossible to assess the overall effects of uncertainties on electricity tariffs because at present there is much debate concerning cost and value of reliability and Quality of Service (QoS), more generally. Regulators will have to take a pro-active role toward establishing rules which begin to align relations between large sources of uncertainties, their effects, and the associated prices. This recommendation goes far beyond wind power issues, and ranges across vast temporal horizons, including shorter term operations planning and longer term investment planning under uncertainties. As long as there is a lack of such mechanisms, it will be impossible to predict the effects of uncertainties on customers. The only prediction is that these effects are unbundled over space and time, and because of this there is much more volatility than in the bundled industry in which correlations of demand variations are accounted for to a large extent. The cost of managing uncertainties in a largely unbundled way is likely to be unacceptably high and will exceed any potential benefits.

III. Possible Solutions to Integrating Wind Power for its Efficient Utilization

The picture is not as bleak as one may be led to believe based on the discussion up to this point. However, in order to overcome major missed opportunities which are caused by the large variations in wind power, one must revisit state-of-the-art literature concerning operations paradigms for better utilization of system resources under uncertainties.

In particular, it is essential to begin to rely on multi-temporal automation and control beyond current AGC. The ideas suggested and illustrated in [1], [2] lend themselves naturally to dealing with the key issue caused by uncertainties. In [1] a paradigm was put forward for automating control of slower deviations in response to tie-line flow deviations around their schedules. This would be done in addition to faster AGC. The major benefit from such schemes would be that the control correlates changes between samples, and it smooths out the effects of fast deviations in error. This is the fundamental difference between doing static deterministic feed-forward dispatch, one time interval at the time, without relating to what happened previously, on one hand, and the automated control to manage stochastic disturbances, on the other. Electricite de France (EdF) has long recognized this distinction, primarily in light of their automated pilot point based voltage regulation [8]. The first author has extended with her collaborators in [1] and jointly with EdF similar concepts to frequency control beyond short term AGC. Given tremendous wind power swings, one can not manage each swing without taking into consideration which units did what earlier. Otherwise, there will be un-necessary wear-and-tear to an extreme. Ideas put forward by Makarov in [2] are Model Predictive Control (MPC) based, and are very similar in nature to the ones suggested in [1] and implemented for voltage regulation by EdF. We conjecture that a pro-active approach to improved automated regulation over look-ahead time horizons could be extremely beneficial for:

- Reducing the number of unit commitment/economic dispatch controllable power plants;
- Reducing the regulation reserve.

Such an approach could go a very long way toward beginning to reap benefits of wind power in a very efficient way. A possible approach would be analogous to the one proposed for defining an ancillary service market for frequency control in [4], with the only difference that the source of uncertainties are wind power swings in addition to the demand swings, and the regulating units could be controllable power plants as well as controllable load [9], [10]. Moreover one could make use of plug in hybrid vehicles as a load that could be shaped to absorb some wind generation production during light load periods. In order to truly benefit from such unconventional balancing technologies, the entire concept of balancing supply and demand must be revisited. In particular, as the industry restructures and the control area loses its fundamental role [11], it is essential to implement more distributed regulation schemes. This may turn out to be particularly relevant when wind resources are distributed at various geographical locations.

We strongly believe that without schemes of this kind in place, it remains impossible to manage causes and effects of uncertain supply/demand efficiently. On the other hand, pursuing active deployment of next generation automated regulation could turn the operational risks associated with large penetration of wind power into exciting solutions.

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