




Advanced Unit Commitment Strategies for the U.S. Eastern Interconnection

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Advanced Unit Commitment Strategies for the US Eastern Interconnection

Erik Ela, Peter Meibom, Rüdiger Barth, Aidan Tuohy, Michael Milligan

***Abstract*--**With increasing penetrations of wind power on the eastern interconnection of the United States, much research has been discussed on how the increased uncertainty may change how the system is operated. In particular, unit commitment programs which decide what units need to be started up in order to meet the changing demand at least cost may need to have modifications in order to reduce costs and improve reliability on a power system with increasing uncertain variables. This paper outlines a study undertaken for the U.S. Eastern Interconnection in which different advanced unit commitment strategies were simulated for three different years to evaluate the benefits that may occur from using these strategies as an operational tool.

***Index Terms*--**Power system operations, unit commitment, stochastic planning, wind power, power system planning

I. Introduction

Different unit commitment methods and strategies with high penetrations of wind power have been an ongoing research topic in recent years. With the uncertainty present in wind power and wind power forecasts, it is important to plan the system to be robust and efficient towards multiple uncertain scenarios. It is also important to make best use of wind power forecasts, realizing they generally improve in accuracy as time horizons become nearer and often before ultimate decisions have to be made. The National Renewable Energy Laboratory, along with RISO DTU, the University of Stuttgart IER, and ECAR pursued an evaluation of these different unit commitment techniques using the Eastern Interconnection of the United States as the study area.

The team used the WILMAR tool in order to analyze the different affects that are seen by advanced unit commitment techniques and wind power and load uncertainty on the power system [1]. The tool has been widely successful in studies performed in Europe [2]-[4]. Its main advantages as a planning tool are its stochastic unit commitment algorithm and its rolling planning technique. Stochastic unit commitment refers to an algorithm that determines the generating units that should be committed in order to satisfy the predicted outcomes of multiple scenarios which are based on stochastic variables. The commitment of units that have long start times must be made in advance of the actual operating hour and therefore these unit commitment decisions must be made to be robust so that they can meet the demand of each predicted scenario. The stochastic unit commitment also minimizes the expected cost and therefore the decisions are based on the probability of each outcome to occur. Rolling planning refers to the capability to update the unit commitment frequently throughout the day. Since forecasts of wind and load achieve better accuracy the closer they are made to real-time, the unit commitment decision can be adjusted to be more efficient as the better information becomes available, as long as the generating unit did not receive the binding startup decision yet. Since most systems in the U.S. and in Europe solve deterministic unit commitments with one expected value and are only generally updated once per day, this tool can give insight into how more advanced techniques can improve a power system which has more uncertainty.

The WILMAR tool includes two components. The scenario tree tool (STT) is a program that creates the probabilistic wind and load forecasts, as well as demands for stochastic reserve. The STT uses the standard deviation of wind plant and load errors as a function of look-ahead time horizon and correlation factors between wind plants based on their distance to determine a large set of possible outcomes with associated probabilities. These are reduced to include a two stage, six branch scenario tree for each planning cycle. The planning cycles for the rolling planning case are done every three hours, with the first three hours being deterministic with realized values, and the next twelve to thirty-six hours being stochastic forecasts. The STT also calculates the replacement reserve based on forecast errors and this reserve is dependent on how the final scenario values were reduced. The second component of the model is the scheduling model. The Scheduling Model (SM) is an optimization model that uses the outputs of the STT as inputs along with other generation and transmission data to minimize the expected production cost. It is usually run as a mixed integer linear programming but due to the large dataset of the U.S. Eastern Interconnect, a continuous Linear Programming approximation was used for this study.

This study was a successor to the Eastern Wind Integration and Transmission Study (EWITS) [5]. The EWITS study analyzed the operational impacts of 20-30% wind power on the Eastern Interconnect and evaluated specific transmission expansion plans. This results in over 225,900 MW onshore and over 16,000 MW of offshore wind plant capacity throughout the Eastern Interconnect. The study did use a production cost model that was deterministic in nature. For the advanced study discussed in this report, the team focused much less on transmission impacts, total costs, and operational requirements needed, but focused entirely on the benefits and impacts of using different unit commitment strategies and how these are affected by the uncertainty of wind power.

This study summarizes the methodologies, results, and further research needs from this study. Section II discusses the detailed methodology used in both the STT and the scheduling model. Section III discusses the data used and results of the study. Section IV then discusses the issues and further research needs involved with the study and the topic of advanced unit commitment techniques. Section V is a brief conclusion to the paper.

II. WILMAR Model Methodology

The WILMAR Planning Tool is used to analyze the consequences of wind power on the Eastern Interconnect. The WILMAR Planning tool consists of a number of sub-models and databases as shown in fig. 1. The main functionality of the WILMAR Planning tool is embedded in the STT and the SM.

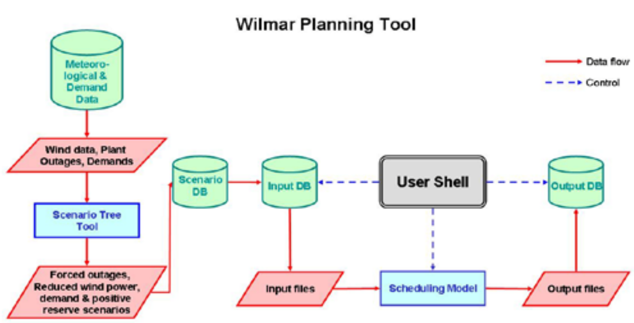

Fig. 1. Overview of the WILMAR planning tool.

A. *Scenario Tree Tool*

The Scenario Tree Tool generates stochastic scenario trees containing three input parameters to the Scheduling Model: the demand for positive reserves with activation times longer than 10 minutes and for forecast horizons from 1 hour to 36 hours ahead (i.e., replacement reserve), wind power production forecasts and load forecasts. The main input data for the Scenario Tree Tool is wind speed and/or wind power production data, historical electricity demand data, assumptions about wind production forecast accuracies and load forecast accuracies for different forecast horizons and regions. Additionally, simulated time-series of forced outages of conventional power plants are generated.

For load and wind power forecast errors, Monte-Carlo simulations are carried out taking into account the individual forecast error characteristics dependant on the forecast horizon. These Monte-Carlo simulations are based on Auto Regressive Moving Average (1,1) (ARMA(1,1)) time series models [1]. It is assumed that the distribution of wind speed errors follows a Gaussian distribution [7]. Further, spatial correlations of wind speed forecast errors as observed in the Eastern Interconnect are explicitly taken into account [8]. In order to generate wind power production and load scenarios, the sample paths of wind power and load forecasts errors are added to historical time series of wind power production and load time series, respectively.

Load and wind power production forecasts are treated independently of each other, whereas the demand for replacement reserve corresponds to the 90th percentile of the total forecast error of load and wind power production. The calculation of the replacement reserve demand by the Scenario Tree Tool enables the WILMAR Planning tool to quantify the effect that partly predictable wind power production has on the replacement reserve requirements for different planning horizons (forecast horizons).

For each planning period, one thousand scenarios of forecasts are generated. Yet such a large number of forecast scenarios cannot be treated with the stochastic Scheduling model. Hence, the number of forecast scenarios is reduced by consideration of the similarity of individual scenarios. Afterwards, based on the remaining scenarios that still form one-stage trees, two-stage scenario trees are constructed by deleting inner forecasts and creating branching within the scenario trees [9]. The individual demand for replacement reserves of one branch of the resulting tree considers the forecast errors of all wind power and load scenarios that have been reduced to this branch. Finally, one scenario tree consists of a forecast of wind power production, load and replacement reserve with an associated probability expressing the weight that the forecast has when calculating the expected costs, i.e. how likely the forecast is judged to be.

Forced outages can be described for each individual power plant with an hourly time resolution. The occurrence of forced outages in a certain hour is simulated with Semi-Markov chains describing the alternating process between the availability and the unavailability state of a power plant [10]. Failure and repair rates are thereby expressed with the mean time to failure and the mean time to repair [11], [11].

B. *The Scheduling model*

The Scheduling model is a mixed integer, stochastic, optimization model with the demand for replacement reserves, wind power production forecasts and load forecasts as the stochastic input parameters, and is solved at hourly time-resolution. The model minimizes the expected value of the system operation costs consisting of fuel costs, start-up costs, costs of consuming CO2 emission permits and variable operation and maintenance costs. The expectation of the system operation costs is taken over all given scenarios of the stochastic input parameters. Thereby it has to optimize the operation of the whole power system without the knowledge which one of the scenarios will be closest to the realization of the stochastic input parameter. Hence, some of the decisions, notably start-ups of power plants, have to be made before the wind power production and load (and the associated demand for replacement reserve) is known with certainty. The methodology ensures that these unit commitment and dispatch decisions are robust towards different wind power prediction errors and load prediction errors as represented by the scenario tree for wind power production and load forecasts.

The demand for positive reserves (including contingency reserve, regulation reserve, and the replacement reserves) determines together with the expected values of load forecasts and wind power forecasts and the technical restrictions of power plants, the day-ahead unit commitment and day-ahead power exchange between regions planned for up to the next 36 hours. The realized load and wind power production together with the technical restrictions of power plants and any forced outages determine the actual dispatch of the power plants and the actual power exchange in the operating hour in question. Technical restrictions of power plants are minimum and maximum stable generation level, minimum number of operation hours and shut-down hours, start-up times, piece-wise linear fuel consumption curves and ramp up and down rates. For the consideration of large power systems comprising a large number of power plants, it is possible to introduce into the Scheduling model a linear approximation of the unit commitment and to aggregate similar power plants (depending on type, used fuel and vintage) to avoid the use of integer variables thereby saving calculation time. Because of the large number of generating units (over 7,000 units in all) in the study regions, this approach has been used in this study.

System reserves schedules are treated endogenously within the Scheduling model. Hence, the allocation of individual types of reserves over different power plants represents one of the optimization results. The model handles contingency reserves, upward and downward regulation reserves and replacement reserves. The main division between categories of positive reserves is between spinning reserves that can only be provided by synchronized (i.e., on-line) units due to the short activation times of these reserves, and reserves which can be provided by both synchronized and off-line units with short start-up times (e.g., combustion turbines). In this study half of the contingency reserve and all of the regulation reserve must be spinning. For each spinning reserve category the reserve capability of a unit is restricted by a maximum reserve capability computed by 10 minute ramp-rate and the online capacity minus the generation.

As it is not possible to cover the whole simulated time period with only one single scenario tree, the model is formulated by introducing a multi-stage recursion using rolling planning. Therewith, the unit commitment and dispatch decisions and the planned power exchanges are re-optimized taking into account that more precise wind power production and load forecasts become available as the actual operation hour gets closer in time, and taking into account the technical restrictions (e.g. start-up times, minimum up and down times) of different types of power plants. The resulting production of each power plant and the changes in the production and power exchange relative to the day-ahead production and power exchange plan are calculated for each hour.

In general, new information arrives on a continuous basis and provides updated information about wind power production and forecasts, the operational status of other production and storage units and about the load. Thus, an hourly basis for updating information would be most adequate. However, stochastic optimization models quickly become intractable, thus it is necessary to simplify the information arrival and decision structure in the Scheduling Model. In this study a two stage model is implemented. The model steps forward in time using rolling planning with a three hour step, so a one-day cycle consists of eight planning loops. For each time step new forecasts (i.e. a new scenario tree) that consider the change in forecast horizons are applied. This decision structure is illustrated in fig. 2 showing the scenario tree for two planning periods. For each planning period a two-stage, stochastic optimization problem is solved having a deterministic first stage covering 3 hours, and a stochastic second stage with six scenarios covering a variable number of hours according to the rolling planning period in question. Hence, the scenario tree represents a decision structure where the system operator performs unit commitment and dispatch assuming perfect knowledge about the realized wind and load in the first three hours, and uncertain knowledge about wind and load in subsequent hours. Every three hours, there is the possibility to change the planned unit commitment and dispatch and power exchange for future hours within the limits provided by start-up times, minimum operation times and minimum shut-down times as a response to receiving updated information about the status of the power system as the operation hours in question gets closer in time. The perfect foresight assumption for the first three hours is necessary for the model, but to get a realistic unit commitment, the wind and load forecast errors within the first three hours contribute to the demand for replacement reserves in the first three hours.

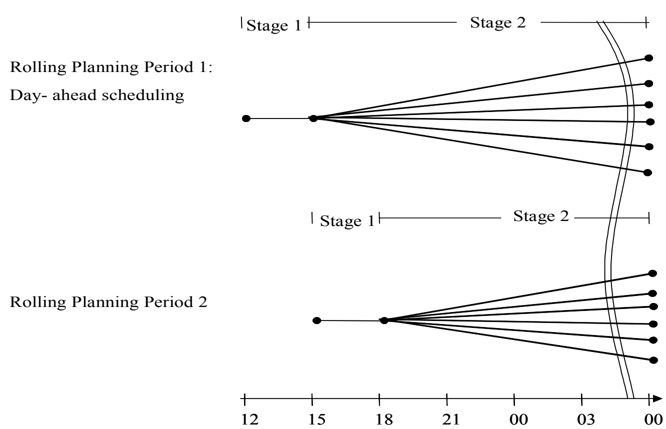

Fig. 2. Illustration of the rolling planning and the decision structure in each planning period.

The rolling planning proceeds as follows: Planning loop 1 starts at 12 pm on day one and covers the 36 hours until the end of day two. The forecast horizons involved are up to 36 hours ahead. The day-ahead scheduling and power exchange is determined in Planning period 1, as well as the realized unit commitment and dispatch and power exchange for the first three hours in the planning loop, which happens after realization of the stochastic parameters. Furthermore unit commitment and dispatch and power exchange plans covering each scenario for the individual outcome of wind power, load and demand for replacement reserve are made.

In Planning loop 2 to 8 the optimization period always ends at the end of day two, i.e. the forecast horizon of the optimization period is reduced with 3 hours in each planning loop, see Figure 2. These planning loops take as a starting point the day-ahead dispatch schedules determined in planning loop 1 when rescheduling the unit commitment and dispatch and power exchange decisions due to updated forecasts. The realised unit commitment and dispatch and power exchange for the first three hours in each planning loop is calculated. Rescheduling plans are made for the total forecast horizon and covering each scenario of the individual outcome of the load minus wind. In planning loop 9 a new day-cycle starts now covering from 12 pm (day two) to the end of day 3.

III. Eastern Interconnection Study Results

This study used almost identical data to that which was used in the EWITS. The study was run for wind and load data of 2004, 2005, and 2006, but was scaled to a 2024 load predictions and for each of the wind scenarios. The wind plants were based on the EWITS scenario 2, which had a distribution of wind power in the Midwest as well as offshore on the east coast. In EWITS, deterministic wind forecasts were used for the unit commitment program and therefore this data was analyzed to understand the error impacts of the 4 hour-ahead, 6 hour-ahead, and day-ahead forecasts to come up with an error distribution which was a function of time horizon. For instance, fig. 3 shows the wind speed errors as a function of time horizon for the first 20 hours for different regions for the year 2004. It can be seen that the forecast error mainly increases during the first few forecast errors and steadily after that.

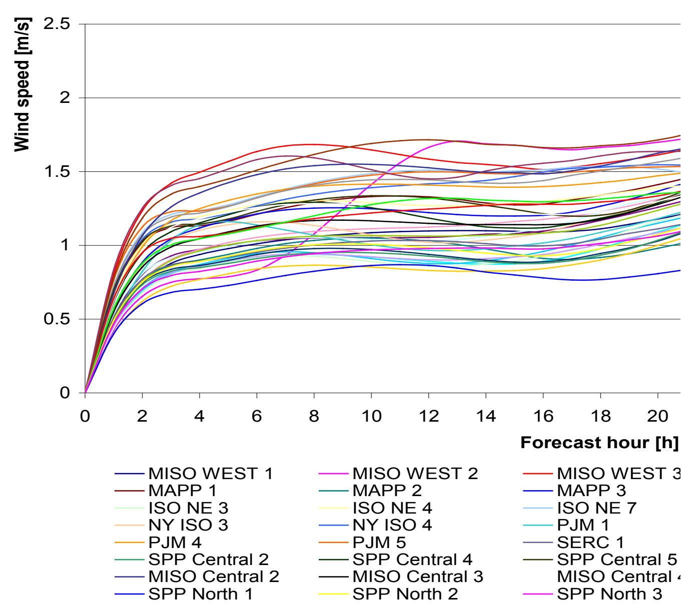

Fig. 3. Standard deviation of wind speed forecast error dependant on forecast horizon given in m/s.

Reserve requirements were also primarily based on EWITS analysis. Portions were left out from the EWITS requirements noting that these would be calculated as a stochastic variable in the replacement reserve requirement. Reserves were hourly requirements and could not be supplied by wind generation. 90% of all uncertainty caused by the wind and would have to be covered by the replacement reserves which could be from offline units. Uncertainty based on forced outages of conventional units was dealt with deterministically with contingency reserves in which 50% was required to be spinning. Regulating reserves are capacity that must be set aside for both upward and downward net load changes referring to units with AGC. All of the regulating reserve is required to be spinning.

The transmission network is represented by splitting the geographical area modeled into a number of model regions, with each model region containing a number of production and storage units and having scenario trees of load forecasts, wind power production forecasts and demand for replacement reserves. The model regions are connected by transmission lines described by a transmission capacity and an average loss which were input from the EWITS power flow limits analyzed. DC load flow calculations are not to be used in this study. The grid within each model region is only taken into account as an average distribution loss, which in this study is part of the electricity load time series.

This data was used as input into the two models. For the STT, probabilistic wind and load forecasts were created for every hour of the three years and for every planning loop instance. Fig. 4 shows an example planning loop of the residual load (load minus wind). This figure displays the residual load for the PJM market area for each of the 6 scenarios, as well as the expected outcome (probability weighted average of scenarios), and the actual realized value. One can see from this figure that the first three hours are deterministic and represent the realized values. It can also be seen that the further one goes out in time, the more uncertain the net load becomes (the wider the range of the scenarios). These time series are created for every region and for every planning loop for the three study years.

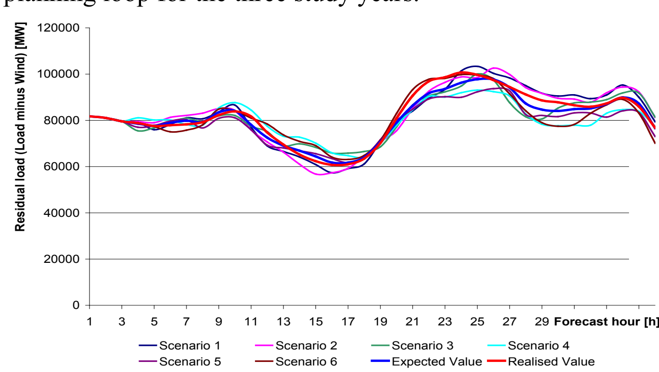

Fig. 4. Example day-ahead forecast scenario tree for the market region PJM given in MW.

Another key input from the STT, is the demand for replacement reserves. In many of the reliability standards and market requirements today, reserve demands are constant in day-ahead time frames and real-time. However, with wind power, the level of uncertainty decreases the closer you operate to the real-time. Therefore, the demand for replacement reserve is a function of forecast horizon, noting that the closer to real-time the less reserve capacity that must be kept for wind and load uncertainty. Fig. 5 shows the demand for replacement reserves for different regions for this study.

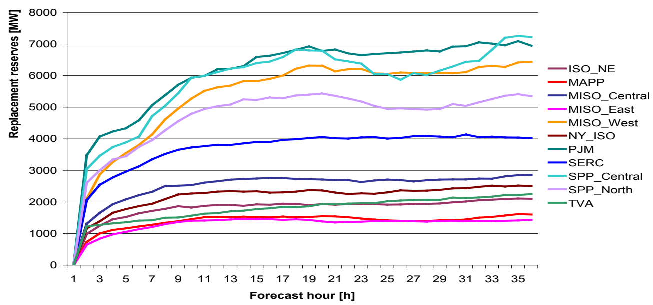

Fig. 5. Average demand for replacement reserves dependant on the forecast horizon for the individual market regions given in MW.

In order to understand the different impacts of different unit commitment strategies, the eastern interconnect was simulated for three different cases for each year. The first is a deterministic unit commitment where the unit commitment can be updated every 3 hours (OTS). The second is a stochastic unit commitment where all units that have start times greater than 1 hour are updated once per day, for instance in the day-ahead market (UCDAY). The third is a stochastic unit commitment where the unit commitment can be updated every three hours (STOC). Therefore the benefits and impacts of stochastic unit commitment can be seen by comparing STOC with OTS, and the benefits and impacts of rolling unit commitment updates can be seen by comparing STOC with UCDAY.

IV. Conclusions

The main difference between the WILMAR model and other unit commitment modelling approaches with wind power is the usage of rolling planning allowing for intraday unit commitment. Our model experiences have shown that modelling of the start up times of units become very important for the results when using intra-day commitment in combination with multiple wind and load input scenarios. The optimisation period of each planning period probably needs to be significantly longer than the start-up time of the slowest units in order to get satisfying unit commitment schedules. Future research will investigate the interplay between the length of optimisation periods, the frequency of intra-day recommitments and the representation of start-up times.

The results of this study show great benefits of stochastic planning and rolling updates to the planning. The rolling updates that provide intra-day unit commitment re-optimization seem to show more benefits over all than the use of stochastic unit commitment. The results were given for the entire Eastern Interconnect and some approximations were used in order to solve the extremely computational intensive problem in a reasonable amount of time. These conclusions give a good benchmark to how these strategies might improve operations and reduce costs in the operational time frame. Further work should evaluate specific regions with more explicit representations to get more information on the benefits and feasibility of these advanced techniques.

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VI. Biographies

Erik Ela received the B.S.E.E degree from Binghamton University and the M.S.E.E. degree in Power Systems at the Illinois Institute of Technology. He joined the National Renewable Energy Laboratory's grid integration team to work on different wind integration issues. His experience lies mostly in different topics relating to grid operations, controls, and market operations. Erik previously worked for the New York ISO developing and improving products in the energy markets and operations areas.

Peter Meibom is Senior Scientist in RISOE National Laboratory for Sustainable Energy, Technical University of Denmark. He received a M.Sc. Phys in 1996 from Roskilde University and a Ph.D. in 2001 from Technical University of Denmark. His research interest is modeling of energy systems characterized by a large share of renewable energy sources in the system.

Rüdiger Barth studied mechanical engineering at the University of Stuttgart, Germany and received his diploma degree in 2003. Since 2003 he works at the Institute of Energy Economics and Rational Use of Energy at the University of Stuttgart, Germany. Since 2007 he is head of the group electricity system analysis. His research interest is the integration of decentralized generation and of intermittent power sources into electricity systems.

Aidan Tuohy received a B.E. degree in Electrical and Electronic Engineering from University College Cork in 2005. He is currently studying for a Ph. D. degree in the Electricity Research Centre, University College Dublin, during which he has also spent time in Risoe-DTU, Denmark and the National Renewable Energy Laboratory. His research interests are in operational, planning and policy issues for power systems with high wind penetrations.

Michael Milligan is part of the Transmission and Grid Integration Team at the National Renewable Energy Laboratory. He has authored or coauthored more than 100 papers and book chapters and has served on numerous technical review committees for wind integration studies around the U.S. Michael is a member of the leadership team of the NERC Variable Generation Task Force, member of WECC's Variable Generation Subcommittee, member of the IEEE Wind Power Coordinating Committee,, and served on the Western Governors' Association Clean and Diverse Energy Wind Task Force. Michael has M.A. and Ph.D. degrees from the University of Colorado, and a B.A. from Albion College.

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