The State-of-the-Art of the Short Term Hydro Power Planning with Large Amount of Wind Power in the System

Yelena Vardanyan, Mikael Amelin

Electric Power Systems, Royal Institute of Technology

Teknikringen 33, 10044 Stockholm, Sweden

yelena.vardanyan@ee.kth.se

amelin@kth.se

***Abstract*—The amount of wind power is growing significantly in the world. Large scale introduction of wind power in the power system will increase the need for improved short term planning models of hydro power, because additional variations are introduced in the system. This huge amount of uncertainties in the power system will cause changes in the power market and there will be a value of advanced planning techniques, that will allow more flexibility in hydropower generation by taking into account stochastic nature of spot and regulating markets, water inflow, future water value and so on.**

The application of multi-stage stochastic optimization in the planning of the daily production of hydro power is not wholly discovered and requires further research. The complexity of the mathematical programming of the short term hydro power production including several type of uncertainty, while keeping the problem size solvable, challenges the power system researchers.

This paper overviews the literature in the field of short term hydro power planning in power systems with large amount of wind power.

I. Introduction

After the deregulation of the electricity market, where electricity is traded in a competitive way optimal short-term hydro power planning become even more important and essential task for a hydropower producer. In a deregulated settings market players have more difficulty to reach to the desirable information and construct their production plans based on that. In general, there are a lot of uncertainties in the system the hydropower producer has to take into account while constructing price-driven optimal production plan. Some of those uncertainties are water inflow rate to the reservoirs, electricity demand, market prices for the electricity and so on. Besides, recently there is a huge level of uncertainty introduced to the power system related to the continuously growing high level integration of renewable power resources like intermittent wind power, which is shaping current and future power market and industry. The intermittency behaviour of wind power makes very hard to predict and manage the output energy of the wind farms, therefore considering wind power as uncertain power source. The amount of wind power is continuously increasing in the world and making the planning of hydropower production even more challenging. These uncertainties in the power system are interesting for many researchers in the field, who have shifted from the building of the conventional deterministic models to multi-stage stochastic models for short-term hydropower planning to evaluate impact of uncertainties, especially intermittency of wind power.

This paper overviews the literature in the field of short term hydro power planning in power systems with large amount of wind power, providing background to understand the operation of power systems and analysing most of the existing short term hydropower deterministic and stochastic models. The review covers wide range of publications in periodical journals transactions and conference proceedings published after 1990. All papers can be categorized into the following groups: wind power and its impact on power system, reserve requirement of wind integrated power systems, congestion management, short term hydropower planning: deterministic and stochastic models, solution algorithms for a large multi-stage stochastic program. The paper also emphasizes hot topics in the mentioned field and provides discussion in which direction to continue further research.

II. Literature Review

A. *Wind Power and its Impact on Power System*

The renewable energy impact on the power system, particularly wind power impact is huge and interests many researchers in the field. All those impacts are mainly depends on the following factors: the penetration level of wind power, the generation mix in the power system and grid size [1]. The impacts of wind power on the power system can be divided into short and long-term effects. The short-term effects are those which last minutes to hours, whereas the long-term effects have yearly timescale. Example of long-term effect can be the contribution of wind power to the system adequacy: its capability to meet peak load situations in a reliable way. Besides, wind power impact on the power system can be categorized into local or global effects according to the effect size scale.

Although wind power is introducing more uncertainty to the system which creates planning problem for all electricity players in the system, it is always important to emphasize and start from the benefits got from wind power. First, installed wind power can increase the energy reliability and decrease the risk of energy deficit. This is concluded in [2] where L.

Söder analyses the impact of wind energy on the energy reliability in power system where hydro is the dominated power source and in [3] where M. Amelin analyses the wind power contribution to supply adequacy. The same conclusion However, the intermittency behaviour of the wind power can also decrease the energy reliability in different circumstances. Second, wind power can provide voltage control and partially support to primary and secondary control, however it can cause power quality problems creating harmonics and voltage flicker [4]. Installed wind farm can reduce congestion problems on transmission lines; can also reduce transmission losses if wind farm is installed close to the heavy consumption areas. For example, consider two-area system where electricity is mainly produced in one area and is consumed in another area. If the wind farm install in the area where the consumption is higher, it will decrease the congestion on transmission line which transfer electricity from the production area to the consumption area. Unfortunately renewable energy like wind and solar are produced where the source is and transferred to the final customer. Therefore sometimes it can even increase the congestion on the lines. M. Korpaas and others [5] introduce a method for scheduling and operation of wind power storage in electricity market as an alternative to transmission line enforcement or wind curtailment. On the other hand the quality of wind power forecast is not so high; hence large unforeseen variation of wind power production can occur in the system, which must be handled in a financially feasible way. In [6] L. Söder presents a method which simulates potential wind speed outcomes using available wind speed forecast from several areas with the information about the forecast errors correlation in the neighbouring areas. In [7] H. Holttinen discusses the impact of hourly wind power variations on the hourly load following reserve requirements. Beside mentioned above characteristics, wind power creates imbalance cost for the wind farm owners when they make in advance contract. This increases market prices which in its turn effects on other players in electricity market. J. Matevosyan [8] develops new imbalance cost minimization method using stochastic programming, which generates optimal wind power production bids for a short term power market. Finally, stochastic behaviour of wind power production has a big impact on the demand for real time balancing power, as well as on market prices. Those issues are discussed by M. Ollson and others in [9] and [10]. L. Söder and others [11] presents the experience of some regions with high penetration of wind power, describing the consequences if there will be further increase in wind power. Table summarizing wind power impacts on the power system is provided below.

TABLE I
WIND POWER IMPACTS ON POWER SYSTEM

	Local	**Global**
Short -term	1.wind farms can provide voltage support depending on the design (seconds to minutes) 2.wind power can cause power quality problems creating harmonics and voltage flicker	1.increasing need for the real time balancing power imbalance (minutes to hours), 2.can also partially contribute to primary or secondary control,
Long -term	1.wind farm can decrease/increase congestion on the transmission line, 2.can reduce/increase transmission losses,	1.wind power will contribute to the system adequacy, 2.wind farms can create a need for additional investment to enhance a transmission line 3.if conventional unit is replaced by wind farm additional need for reserve power will be needed

B. Reserve Requirement of Wind Integrated Power System

As an environmentally friendly energy source wind power has got prevalent public support, and accordingly wind power integration to the power system is growing significantly. The risk related to keep short term power balance (avoiding frequency deviations) can increase radically and planning of the frequency control reserves (instantaneous, fast and slow) becomes more challenging because of the output uncertainty of the wind power due to its intermittency behaviour. In [14] L. Söder estimates the requirements for instantaneous, fast and slow reserves as well as the available capacity of corresponding reserve type when wind power is introduced to the power system. H. B. Bakken and others [18] describes a new tool to analyse capacity shortage and reserve requirements.

Due to the fluctuations in the wind power, the need for balancing power will increase, which in its turn will increase real-time market prices. Because its flexibility and capability to increase production very fast, hydropower with reservoirs can provide balancing power and earn extra profit. Therefore, there is a value of improved planning tools, which allow the hydropower producer to provide even more flexibility.

In addition, the amount of wind energy that can be integrated in the system highly depends on the available capacity of the conventional units. In order to increase the utilization of wind power and decrease the operation risks there is a need to coordinate different type of generation units properly. According to [19], it is mutually beneficent for hydro and wind power to work together to supply stable electricity. However, the long-term system adequacy can be affected by such kind of synchronization. In [21] R. Karki and others discuss the impact of wind-hydro-thermal coordination on system reliability, and conclude that wind-hydro cooperation can have positive or negative impacts on the system adequacy depending on the size of hydro reservoir and the number of hydro units assigned to cooperate with wind power.

C. Congestion Management

When the transmission network is not capable to transfer electric power according to the market desire as a result we get congestion. Usually wind power plants are installed in the remote areas to avoid obstacles and harvest wind power more efficiently. On the other hand the transmission network may be is not strong enough in remote areas to be able to transfer extra energy. However if there is hydropower plant with sufficient large reservoir installed nearby, it is possible to cooperate which can be mutually beneficiary for both players and leads to use the transmission network in a best possible way. The alternative solutions are to enhance the existing transmission line or to have battery storage for wind power farm when transmission line is congested. Both are costly and not always economically possible. The way the hydropower and wind power owners can cooperate is the following: wind power owner has priority to use available transmission capacity when it is windy. It means in those cases hydropower owner can reduce hydropower generation according to physical limitations of power plants, and use stored water when wind is low and power prices are high. When hydropower plant and wind farm are owned by the same player, the cooperation is straightforward. In the case with separate ownership different cooperating strategies are studied by A. Jäderström and others in [22]. J. Matevosyan [23] presents daily stochastic planning algorithm, under uncertainty of wind power forecast, for a multi-reservoir hydropower system cooperated with a wind farm, in the other words the algorithm tends to decrease wind energy curtailment in the cases when congestion occurs. J. Matevosyan and others in [24] improve the mentioned above planning algorithm in [23] further. New planning algorithm is a two-stage stochastic program with recourse under uncertainty of wind power forecast and power market prices.

D. Short Term Hydropower Planning

On one side decentralized competitive nature of current electricity market and on the other side continuous increase in wind power integration to the power system creates a challenge for a short term hydropower producer to plan and operate hydropower in an optimal way. Due to its flexible and fast generation hydropower is a very suitable power source to balance wind power variations [25]. Since traditional operation rules were working according to centralized optimization, there is a need for new, advanced hydropower planning techniques capable to work under existing requirements. There are a lot of deterministic models to plan short-term hydropower production in the literature. However, researchers' interest to work under uncertainty is noticeable recently.

Deterministic models do not have any random variable and have a known set of inputs which will result in a unique set of outputs. In those models there is no information arriving over time and decisions are made in advance for the whole planning horizon even for long-term planning. In contrast, stochastic programming addresses optimization under uncertainty, and reflects the fact that new information about the uncertain data arrives as time evolves along the planning horizon. According to information flow a multi-stage stochastic program is characterized by partition of decision variables into stages in a way that decisions made for one stage do not affected from the information arriving in following stages. For example [33] introduces two stage stochastic model for bidding strategies of a hydropower producer, where first stage represents bidding process to day-ahead market, while the second stage involves the production aspects after day-ahead market prices are cleared. Probability description about the uncertain data is approximated by a so called scenario tree (e.g. Fig.1).

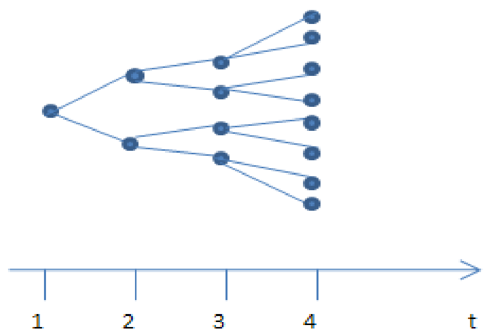

Fig. 1. Example of scenario tree for stochastic case

Table II is summarizing deterministic and stochastic short-term hydropower models. In the literature there are research groups, who work with optimization and its application in power systems and have several consecutive models in the field of short term hydropower planning. The short term hydro planning models described below are representative models.

In [26] K. Z. Shawwash and others develop deterministic optimization model for short-term hydropower scheduling for the third large power sector in Canada, using linear programming. D. E. Castronuovo and others describe optimal daily operational strategy for a wind-hydro power plant considering that wind-power forecast is characterized by some uncertainty [27]. The operation efficiency of the hydro power plants with the small storage capacity highly depends on the head (head effect is negligible for the plants with a large reservoir). Therefore, in order to get more realistic short-term production plan, it is important to introduce head-dependency to the optimization model. In [28] A. Borghetti and others introduce MILP short-term hydropower production plan with head-dependent reservoir. While J. P. S. Catalao and others [29] formulate short-term hydropower planning model using nonlinear optimization and taking into account head-dependency.

TABLE II

SUMMARY OF THE SHORT TERM HYDROPOWER PLANNING MODELS

Deterministic models			
Title	**Objective**	**Uncertainty**	**Solution Methods**
The B.C. hydro short term scheduling, Z. K. Shawwash etc.	To determine the optimal hourly generation and trading schedules in a competitive power market	-	Advanced algebraic modeling language and a linear programming package
An hourly discredited optimization algorithm , E.D. Castronuovo etc.	To identify the optimum daily operational strategy to be followed by wind and hydro generation units	-	-
An MILP approach for short term hydro planning with head effect, A. Borghetti etc.	To find the optimal scheduling of a multiunit pump-storage hydro power station	-	Commercial software
Nonlinear approach for short term hydro planning with head effect, J.P.S. Catalao etc.	To solve the short term hydro scheduling problem considering head dependency	-	Commercial software
Optimal short term hydro scheduling of large power systems, A. Bensalem etc.	To determine the optimal short term operating policy of hydroelectric power systems	-	Augmented Lagrangian method
Stochastic models			
Model	**Objective**	**Uncertainty**	**Solution Methods**
Stochastic hydro- electric unit commitment, A.B. Philpott etc.	To determine which turbine unit to commit in each half of the day	Demand	Approximated by solving a deterministic equivalent linear programming, then solving a stochastic dynamic programming recursion
Power management under uncertainty, N. Gröwe-Kuska etc.	To investigate the weekly cost-optimal generation of electric power in a hydro-thermal generation system	Demand and prices for fuel and delivery contracts	Lagrangian relaxation
Two-stage stochastic planning model, R. Nurnberg etc.	To develop short or mid-term cost-optimal electric power production plan	Demand and prices for fuel and delivery contracts	Lagrangian relaxation scheme, Solving the dual by a bundle subgradient method
Self-scheduling profit maximization problem, A.J. Conejo etc.	To obtain the optimal bidding strategy of a price-taker producer	Price	Commercial software
Short-term hydropower scheduling model, M. Olsson	To manage the trade-off between energy and reserve markets	Real-time balancing market prices	Commercial software
Stochastic joint optimization of wind generation and pumped-storage units, J.G. Gonzalez, etc.	To investigate the combined optimization of a wind farm and a pumped-storage facility	Market prices, wind generation	Commercial software
Two-stage stochastic model , S.E. Fleten etc.	To determine optimal bidding strategy	Spot market prices	Commercial software
Multi-stage mixed-integer linear stochastic model, S.E. Fleten etc.	To develop a short term production plan for a price-taking hydropower	Spot market prices, water inflows	Commercial software

The most important aspects that short-term hydropower producer should take into consideration while developing production plan under uncertainty are the followings: day-ahead commitment (production bidding to spot market), production plan according to day-ahead commitment, bidding strategy to regulating market, water inflow, future water value (up to seven days counted from the delivery day). All those mentioned above points are subject to uncertainty depending on unexpected market changes and unpredictable weather conditions. Multi-state stochastic programming is used in the literature to cope with these uncertainties. In [30] A. B. Philpott and others develop hydro-electric unit commitment model subject to uncertain demand. R. Nurnberg and others [31] present two-stage stochastic model for hydro-thermal systems under the uncertainty of fuel price, electricity price and load. J. A. Conejo and others [32] provide probabilistic structure for a price taking producer to deal with market-clearing prices. M. Olsson [33] introduces stochastic optimization model under uncertainty of regulating market prices for price-taking hydropower producer. S.-E Fleten and K. T. Kristoffersen [35], [36] develop two-stage stochastic optimization models for price-taking hydropower producer. Hydropower producer, who does not have market power, takes market prices which are settled by the other market participants and in general there is no relevant information how those participants will act in the power market. First paper presents two-stage stochastic programming model for optimizing bidding strategies under the uncertainty of the day-ahead market prices. While second paper introduces one-day production plans that keeps a balance between current profits and expected future profits.

Up to now the most existing stochastic models for short-term hydropower planning are reflecting only one type of uncertainty in the system, for example, model which is dealing with the load uncertainty, day-ahead market price uncertainty or real-time market price uncertainty etc.

To have a more realistic production plan model there is a need to address several type of uncertainty at once. For example, to treat real-time market price uncertainties with the future (up to seven days) price uncertainties, or day-ahead market price uncertainties with the water inflow uncertainties. This multi-stage stochastic models will provide better plans, in other words the probability that this models will reflect what is going to happen in the system during the actual hour is high. Therefore, there is a significant need for the further research and development of the multi-stage stochastic models in the field of short-term hydropower planning, introducing more than one type of uncertainty. However, the introduction of more than one type of uncertainty will increase the problem size significantly and sometimes make it unsolvable, which is another challenge for the researchers in the field.

E. Solution Algorithms for a Large Multi-Stage Stochastic program

As it is mentioned above, short-term hydropower scheduling models under uncertainty are great interest because of the decentralized environment of electricity market and tendency to increase wind power integration to the power system. The structure of the stochastic programming is a best fit to optimization problems under uncertainty. In order to model multivariate nature of the random variable those models use a set of scenarios with corresponding probabilities. Hence, multi-stage stochastic models for planning of the power systems are large-scale and contains internality constrains, which is making demanding task to solve it. Sometimes, even recently developed software like CPLEX, designed to solve large-scale mixed-integer problems, fails to solve. Therefore, it is very important to study suggested algorithms which will bring the problem size down, and make the problem solvable within reasonable time. P. M. Nowak and others in [39], [40] present stochastic Lagrangian relaxation approach applied to power systems under uncertainty. N. Gröwe-Kuska and others [41] describe scenario reduction algorithms and scenario tree construction for large-scale problems.

III. CONCLUSION

Modeling new and growing uncertainties related to the wind power and decentralized nature of power and energy industry is an essential issue for smooth operation of power system. This is an important issue for short-term hydropower producer as well, who is intended to find a balance between current profits and expected future profits. Research in this field is not fully explored and needs further efforts. Recently developed successful models for short-term hydropower scheduling are developed under uncertainty of either demand, or spot market prices, or regulating market prices. The introduction of several types of uncertainty to the short-term hydropower planning model with consideration of new market rules will give more realistic and reliable result. However this will significantly increase problem size, which may require more advanced solution algorithms and techniques to bring problem size down and make it solvable. These will be a future challenge for the researchers in those fields.

REFERENCES

[1] J.C. Smith, E. A. DeMeo, B. Parsons, M. Milligan, "Wind power impacts on electric power system operating costs: summary and perspective on work to date", in *Global Wind Power Conference*, 2004.

[2] L. Söder, "Wind energy impact on the energy reliability of a hydro-thermal power system in a deregulated market", in *PSCC*, 1999.

[3] M. Amelin, L. Söder, "The impact of wind power on supply adequacy-experience from the swedish market", *Power &Energy*, vol. 8, Oct. 2010.

[4] J. Matevosyan, "Wind power integration in power systems with transmission bottlenecks", Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden 2006.

[5] M. Korpaas, A.T. Holen, R. Hildrum, "Operation and sizing of energy storage for wind power plants in a market system", *International Journal of Electrical Power & Energy Systems*, vol. 25, pp. 599-606, Oct. 2003.

[6] L. Söder, "Simulation of wind power forecast errors for operation planning of multi-area power systems", in *PMAP*, 2004.

[7] H. Holttinen, "Impact of hourly wind power variations on the system operation in the Nordic countries", *Wind Energy*, vol. 8, pp. 197-218, June 2005.

[8] J. Matevosyan, L. Söder, "Minimization of imbalance costs bidding wind power on the short term power market", in *Proc. IEEE PowerTech*, 2005.

[9] M. Olsson, L. Söder, "Estimating real-time balancing prices in wind power systems", in *Proc. PSCE*, 2009.

[10] M. Olsson, M. Perninge, L. Söder, "Modeling real-time balancing power demands in wind power systems using stochastic differential equations", *Electric Power Systems Research*, vol. 80, pp. 966-974, 2010.

[11] L. Söder, L. Hofmann, A. Orths, H. Holttinen, Y. Wan, A. Tuohy, "Experience from wind integration in some high penetration areas", *IEEE Transactions on Energy Conversion*, vol. 22, 2007.

[12] H. Holttinen, P. Meibom, A. Orth, B. Lang, M. O'Malley, J. O. Tand, A. Estanqueir, E. Gomez, L. Söder, G. Strbac, J. C. Smith, F. van Hulle. "Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration", *International Workshop on Large Scale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms*, 2009.

[13] M. Cailliau, M. Foresti, C. M. Villar, "Risks and solutions for integrating large-scale intermittent renewable sources into the EU electricity system by 2020", *Power &Energy*, vol. 8, , Oct. 2010.

[14] L. Söder, "Reserve Margin Planning in a Wind-Hydro-Thermal Power System", *IEEE Transactions on Power Systems*, vol. 8, 1993.

[15] Y. H. Moon, H. S. Ryu, J. K. Park, "A new paradigm of automatic generation control under the deregulated environments" *IEEE Power Engineering Society Winter Meeting*, vol. 1, pp. 21-25, 2000.

[16] E. Lindgren, L. Söder, "Minimizing regulation cost in multi-area systems with uncertain wind power forecasts", *Wind Energy*, vol.11, pp. 97-108, Feb. 2008.

[17] E. Lindgren, L. Söder, "Power system modeling for multi-area regulating market simulation" in IEEE Power-Tech Conference, 2005, pp 1-7.

[18] H. B. Bakken, A. Petterteig, E. Haugan, B. Walther, "Stepwise power flow to analyze capacity shortage and reserve requirements", in PSCC, 2005.

[19] K.-O. Vogstad, "Utilizing the complementary characteristics of wind power and hydropower through coordinated hydro production scheduling using the EMPS model", in *Proc. NWEC*, 2000.

[20] F. Bouffard, F. D. Galiana, "Stochastic security for operations planning with significant wind power generation", *IEEE Power and Energy Society Genera,l* 2008.

[21] R. Karki, P. Hu, R. Billinton, "Reliability assessment of a wind integrated hydro-thermal power system", in PMAPS, 2010, pp 265 – 270.

[22] A. Jäderström, J. Matevosyan, L. Söder, "Coordination Regulation of wind power and hydro power with separate ownership", Proc. *International Conference in Energy Economics*, 2005.

[23] J. Matevosyan, L. Söder, "Optimal daily planning for hydro power system coordinated with wind power in areas with limited export capability", in *Proc. PMAPS*, 2006.

[24] J. Matevosyan, M. Olsson, L. Söder, "Hydro power planning coordinated with wind power in areas with congestion problems for trading on the spot and the regulating market", *Electric Power Systems Research*, vol. 79, pp. 39-48, 2009.

[25] C. Belanger, L. Gagnon, *Adding Wind Power to Hydropower*, Energy Policy, Vol. 30, pp. 1279-1284, 2002.

[26] K. Z. Shawwash, K. T. Siu, S. O. Denis Busel, "The B. C. hydro short term hydro scheduling optimization mode", *IEEE Transactions on Power Systems*, vol. 15, Aug. 2000.

[27] D. E. Castronuovo, J.A. Pecas Lopes, "On the optimization of the daily operation of a wind-hydro power plan", *IEEE Transactions on Power Systems*, vol. 19, Aug. 2004.

[28] A. Borghetti, C. D'Ambrosio, A. Lodi, S. Martello, "An MILP approach for short-term hydro scheduling and unit commitment with head-dependent reservoir", *IEEE Transactions on Power Systems*, vol. 23, Aug. 2008.

[29] J. P. S Catalao, S. J. P. S Mariano, V. M. F Mendes, L. A. F. M. Ferreira, "Nonlinear optimization method for short-term hydro scheduling considering head-dependency" *IEEE Transactions on Electrical Power*, vol. 20, pp 172-183, 2010.

[30] A. B. Philpott, M. Craddock, H. Waterer, "Theory and methodology: hydro-electric unit commitment subject to uncertain demand", *European Journal of Operational Research*, vol. 125, pp. 410-424, Sep. 2000.

[31] R. Nurnberg, W. Römisch, "A two-stage model for power scheduling in a hydro-thermal system under uncertainty", *Optimization and Engineering*, Vol. 3, pp 355-378, 2002.

[32] J. A. Conejo, J. F. Nogelas, M. J. Arroyo, "Price-taker bidding strategy under price uncertainty", *IEEE Transactions on Power Systems*, vol. 17, Nov. 2002.

[33] M. Olsson, L. Söder, "Hydropower planning including trade-off between energy and reserve markets", in IEEE *Power-Tech*, 2003.

[34] M. Olsson, L. Söder, "Optimal regulating market bidding strategies in hydropower systems", in *Proc. PSCC*, 2005.

[35] S.-E. Fleten, K. T. Kristoffersen, "Stochastic programming for optimizing bidding strategies of a Nordic hydropower producer", *European Journal of Operations Research*, vol. 181, pp 916-928, 2007.

[36] S.-E. Fleten, K. T. Kristoffersen, "Short-term hydropower production planning by stochastic programming", *Computers and Operations Research*, vol. 35, pp 2656-2671, 2008.

[37] A. Bensalem, A. Miloudi, S. E. Zouzou. B. Mahdad, A. Bouhentala, "Optimal short term hydro scheduling of large power systems with discretized horizon", *Electrical Engineering*, vol. 58, pp 214-219, 2007.

[38] J. G. Gonzalez, R. M. R. Muela, L. M. Santos, A. M. Gonzalez, "Stochastic joint optimization of wind generation and pumped-storage units in an electricity market", *IEEE Transactions on Power Systems*, vol. 23, 2008.

[39] P. M Nowak, W. Römisch, "Stochastic lagrangian relaxation applied to power scheduling in a hydro-thermal system under uncertainty", *Annals of Operations Research*, vol. 100, pp 251-272, 2000.

[40] N. Gröwe-Kuska, K. C. Kiwiel, W. Römisch, P. M. Nowak, I. Wegner, "Power management under uncertainty by lagrangian relaxation", in *PM APS*, 2000.

[41] N. Gröwe-Kuska, H. Heitsch, W. Römisch, "Scenario reduction and scenario tree construction for power management problems", *IEEE Power-tech*, 2003.

[42] T. Achermann, (editor), *Wind Power in Areas With Limited Transmission Capacity*, January 2005.

[43] K. Skytte, "The regulating power market on the Nordic power exchange Nord Pool: an economic analysis", *Energy Economics*, vol. 21, pp. 295-308, 1999.

[44] K. Halldorssson, J. Stenzel, "A scheduling strategy for a renewable power marketer", in *IEEE Power-Tech*, 2001.

[45] C. Jauch, J. Matevosyan, T. Achermann, S. Bolik, "International comparison of requirements for connection of wind turbines to power systems", *Wind Energy*, vol. 8, pp. 295-306, Sep. 2005.

[46] J. Matevosyan, T. Achermann, S. Bolik, "Technical regulations for the interconnection of wind farms to the power system", in *Wind Power in Power Systems*, 2005.

[47] —, "The Swedish electricity market and the role of Svenska Kraftnät", Svenska Kraftnät, Tech. Rep. 2007.

[48] M. Olsson, L. Söder, "Modeling real-time balancing power market prices using combined SARIMA and Markov Processes", *IEEE Transactions on Power Systems*, vol. 23, May 2008.

[49] G. S. Miera, P. R. Gonzalez, I. Vizcaino, "Analyzing the impact of renewable electricity support schemes on power prices: the case of wind electricity in spain, energy policy", vol. 36, pp.3345-3359, 2008.

[50] A. Philpott, Z. Guan, J. Khazaei , G. Zakeri, "Production inefficiency of electricity markets with hydro generation", in *Utilities Policy*, 2010.