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Impact of Wind Energy on Cost and Balancing Reserves

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Abstract**—**Wind energy offers a significant advantage such as no fuel costs and no emissions from generation. However, wind energy sources are variable and non-dispatchable. The utility grid is able to accommodate the variability of wind in smaller proportion along with the daily load. However, at high penetration levels, the variability can severely impact the utility reserve requirements and the cost associated with it. In this paper the impact of wind energy is evaluated in detail in formulating the total utility cost. The objective is to minimize the overall cost of generation while ensuring the proper management of the load. Overall cost includes the curtailment cost, reserve cost and the reliability cost, as well as any other penalty imposed by the regulatory authority. Different levels of wind penetrations are explored and the cost impacts are evaluated. As the penetration level increases significantly, the reliability becomes a critical question to be answered. Here we increase the penetration from the wind yet keep the reliability factor within the acceptable limit provided by NERC. This paper uses an economic dispatch (ED) model to incorporate wind generation into the power grid. Power system costs are analyzed at various wind penetration levels using Linear Programming. The goal of this study is show how the increases in wind generation will affect power system economics.

Keywords**—**Balancing Reserves, Optimization, Wind Energy.

I. Introduction

WIND power is growing in a very fast pace as an alternative generating resource. As the ratio of wind power over total system capacity increases, the impact of wind on various system aspects becomes significant. Due to the variability and uncertainties of wind, the integration of wind have impacts on reliability, operating efficiency, power quality and many other aspects of power systems [1]. The power system must increase its flexibility in both generation and transmission to accommodate the wind energy production. As wind power penetration rate grows, these impacts become more significant. With the Department of Energy's (DOE) plan to increase alternative energy to 20% by 2030 the power market has seen a large increase in the development of wind harvesting technology. From 2006 to 2010 the installed wind capacity in the United States increased from 12 GW to 40 GW [2]. This increase can be contributed to the Federal Production Tax Credit, state renewable portfolio standards, and the favorable economic and environmental characteristics of wind energy compared to other generation methods [3]. Increasing the amounts of variable generation methods (i.e. wind) significantly impacts the stability and cost of operating the power grid. Increased costs are the result of additional regulation services, which are caused by high variability and uncertainty in forecast predictions, and increased maintenance costs for other units.

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The production cost study was evaluated using the Integer Linear Programming software. The goal of the program is to ensure the energy demand is met while minimizing cost. In addition to the operating reserve, some system margin in excess of the system peak demand is required and this will be affected by the level of wind penetration. Generally a 20% surplus energy is required for maintaining the same level of reliability [1].

Curtailment is discarding the energy and it results in economic penalty on variable sources which becomes increasingly important at high penetration. In order to access the economics of Wind Energy generation, it is first necessary to compare the costs of building and operating such plant in comparison to those of conventional generation. Wind energy productivity (kWh per KW) of plant varies significantly with the resource.

The Conventional generator with the load is described in detail in Appendix 1. The wind turbine and the wind farm specification are given in Appendix 2. Appendices 3 and 4 describe the wind installation cost and wind turbines specifications respectively.

II. Cost Analysis

An economic dispatch (ED) model was used to evaluate the cost involved with adding wind generation to the power system. ED involves finding the optimum allocation of available power output from the available generators [4]. The generation level must always equal the demand of the load plus any energy losses in the power system. In the system the ED equations are only available for a given time period, during this time period the model must account for the reserve that is needed to accommodate fluctuations in wind power generation. The ED equations used in the model can be seen below [5]. The total cost comprises different sub costs which makes an overall system costs. They are identified as follows:

A. Conventional Cost

$$C_t = \sum_{i=1}^{ng} CG_i = \sum_{i=1}^{ng} a_i + b_i P_i + \frac{c_i P_i^2}{2} \quad (1)$$

where a_i, b_i, c_i are the Cost Coefficients for the i[th] conventional unit.

B. Wind Integration Cost

$$CW_i = d_i \left(W_{fi} w_i + W_{fi} \right) \quad (2)$$

where d_i =Cost Coefficient for i[th] wind facility.

C. Reserve Cost

$$CR_i(\mathrm{r}) = \mathrm{k}_R\, r \quad (3)$$

where k_R = Cost Coefficient for Balancing Reserve.

D. Curtailment Cost (Over Supply)

$$COS_i = k_{pi}\left(W_{ac,i} - W_{fi}w_i - W_{fi}\right) \quad (4)$$

where k_{pi} = Penalty Cost Coefficient for Over Generation of the i^{th} wind facility.

E. Under Supply Cost

$$CUS_i = k_{ri}\left(W_{fi}w_i + W_{fi} - W_{ac,i}\right) \quad (5)$$

where k_{ri} = Reserve Cost Coefficient for Under Generation of the i^{th} wind facility.

The objective of this paper is to minimize the Total Cost which is the sum of all the above cost and is represented by:

$$\min\left(\sum_i CG_i + \sum_i CW_i + \sum_i CR_i + \sum_i COS_i + \sum_i CUS_i\right) \quad (6)$$

When the NERC reliability factor was incorporated in to our equation to maintain the steady load flow, the equal amount as the wind penetration percentage were kept as reserve to maintain the same level of reliability. The modified equation is

$$minimize[OC(P_{gi}, w_i, r), CPS(r)] \quad (7)$$

Subject to

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad (8)$$

$$0 \leq W_{fi}w_i + W_{fi} \leq w_{Ri} \quad (9)$$

$$\sum_{i=1}^{M} P_{gi} + \sum_{i=1}^{N}(W_{fi}w_i + W_{fi}) = L \quad (10)$$

$$\int_{\frac{-r}{2}-V_{th}}^{\frac{r}{2}+V_{th}} E_S(L_C)dL_c \geq 0.9 \quad (11)$$

where CG = Cost of Conventional Generation; CW = Cost of Wind Generation; CR = Cost of Reserve; COS = Cost of Over Supply; CUS = Cost of Under Supply; OC = Combined operating costs of conventional units, wind generators, and reserves; CPS =Projected percentage of control performance standard violations; P_{gi} =Power output of the i^{th} conventional unit; w_i = Percentage deviation between the scheduled output of the i^{th} facility and its forecast; r = Capacity of balancing reserves; W_{fi} =Forecast of the i^{th} wind facility; w_{ri} = Rated capacity of the i^{th} wind facility; M = Number of conventional units; N = Number of wind facilities; E_S (L_C) =Probability density function of schedule of error of L_C with respect to actual output.

When evaluating the operational costs of the power grid the model took into account the cost of balancing reserve capacity, under generation penalties, over generation penalties (curtailment), and minimum and maximum energy production for each generator. The constraints for the generators can be seen in Appendix 1. This model incorporates penalty for under generation in the form of reserve cost which should have NERC's Reliability standard score of 90%.

Based off of these constraints the program was developed and the power system cost was evaluated. The cost for a wind 320 MW wind farm was based off of a 20 year life wind turbine. Wind farm costs included transmission costs, fuel costs, reserve costs, and installation costs. Values used to determine costs can be seen in Appendix 3 and are found in [6].

III. Power Flow and Stability Analysis

The power flow analysis is performed using Power System Analysis Toolbox (PSAT) [7]. This analysis is performed to test the bus system for voltage stability and power flow stability. The gradual penetration of wind energy was introduced in the steps. At first 10% of the total generating capacity of the conventional capacity was introduced and the power system analysis was performed to check the stability. The analysis was also performed for 15 and 20 % of the conventional capacity. The circuit layout for the simulation is shown in Fig. 1.

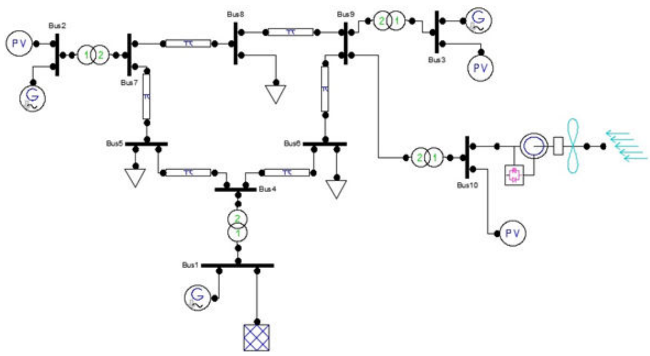

Fig. 1 IEEE 9 bus system of WSCC with wind integrated

IV. Experiments and Results

A. Cost Analysis

In the optimization program the IEEE 9 bus system was utilized. This system is situated within the WECC (Western Electric Coordinating Council) and falls under BPA (Bonneville Power Administration). The total current day load is 315MW and generation capacity totals 320MW. Out of the 9 buses, 3 have generating units and 3 buses supply the load. The goal in the program is to add Wind to support this scenario to reduce the cost of conventional energy generation and reduce the overall operating cost. Cost evaluation was performed with the system operating in an isolated mode, meaning the project is only concerned with this IEEE 9 bus, leaving the other part of the power system out of consideration (9 bus Island operation). Various levels of Wind penetration have been evaluated. If we have less than 5% of wind, then there is no cost increment to the system [8]. Above 5% the extra cost of running the adequate operating reserve must be considered. This cost is reflected in the customer's monthly bill. This increment is the contribution for maintaining the same level of reliability. Above 20% of Wind penetration, some conventional generators have to be shut down, or for the reliability sake, most of the Wind generation units have to be curtailed.

TABLE I
POWER FLOW RESULTS FOR DIFFERENT LEVEL OF WIND PENETRATION

SN	Wind Penetration in Percent	Power Flow		Load Flow		Losses	
		Real	Reactive	Real	Reactive	Real	Reactive
1	0	3.1799	-0.00515	3.15	1.15	0.02987	-1.1552
2	10	3.1813	0.00941	3.15	1.15	0.03128	-1.1406
3	20	3.1842	0.02556	3.15	1.15	0.03416	-1.1244
4	30	3.2207	0.71617	3.15	1.15	0.07065	-0.43383

TABLE II
COST OF TOTAL GENERATION WITH DIFFERENT LEVEL OF WIND

SN	Percentage of Wind Penetration	Conventional Generator, MW		Wind Generator, MW	Storage, MW	Cost without storage, $	Cost with storage & System Operator owns the Wind Farm, $	Cost with storage &, System Operator does not own the Wind Farm, $
		G1	129					
1	0 %	G2	128	0	0	22996.1	N/A	N/A
		G3	63					
		G1	125					
2	10 %	G2	100	32	32	16921.4	17241.4	17401.4
		G3	63					
		G1	116					
3	15%	G2	93	48	48	14994.2	15474.2	15714.2
		G3	63					
		G1	108					
4	20%	G2	85	64	64	13210.2	13850.2	14170.2
		G3	63					

This protects the power system against sudden spikes or drops in Wind generation. In the optimization model varying levels of penetration were used to see how the overall cost behaves (including the curtailment cost and the reliability cost and any other penalty imposed). A way to save part of the curtailment cost would be by considering storage or a reserve. The current model incorporates penalty for under generation in the form of reserve cost which should have NERC's Reliability standard score of 90 percent [9]. The cost optimization model uses the 'Economic Dispatch Model', and currently analyzes the system with or without storage. The program also incorporates the curtailment charge for over generation. After running optimization simulations it was determined that wind integration reduces the overall operation and production cost. A Linear Integer Programming is used to calculate the optimum cost. Gurobi [10] was used as ILP software.

The need for reserve was determined as the same amount of wind energy introduced into the grid. About 32MW of reserve is feasible from the battery storage such as NaS battery [11]. Any increment from this value demands a different storage type which is complicated and more resourceful than the battery reserve. A spinning reserve of conventional generator has to be at standby and has to be modeled as the active conventional generator in terms of cost. But for this study purpose we have extended the same principle as using 32MW battery bank for the increased penetration of the wind and then evaluated the operating cost. The cost factor a, b, c, d, k_r, k_{pi}, and k_{ri} are used from [4].

B. Stability Analysis

The analysis shows that none of the lines constraints are violated. The voltage profile at each bus for different wind energy penetration is well within the limit. The voltage profile is depicted in Fig. 2 for different scenarios. Thus adding wind to the existing grid has no negative impact on the operation of the grid. Table I shows the Power flow, load flow and the system losses for the different level of wind penetrations.

Fig. 2 shows the voltage profile at all busses for conventional 3 generator 3 load system at (a), conventional 3 generator, 3 load and 10 percent wind at (b), conventional 3 generator, 3 load system and 15 percent wind at (c) and 3 generator, 3 load and 20 percent wind at (d). The voltages at all buses are well within the limit of 0.9 to 1.10 p.u.

Fig. 3 shows the plot of the cost without storage, cost with storage and system operator owns a wind farm and cost with storage and system operator does not own the wind farm against different penetration level of winds. It can be seen that the cost is declining as the wind penetration increases.

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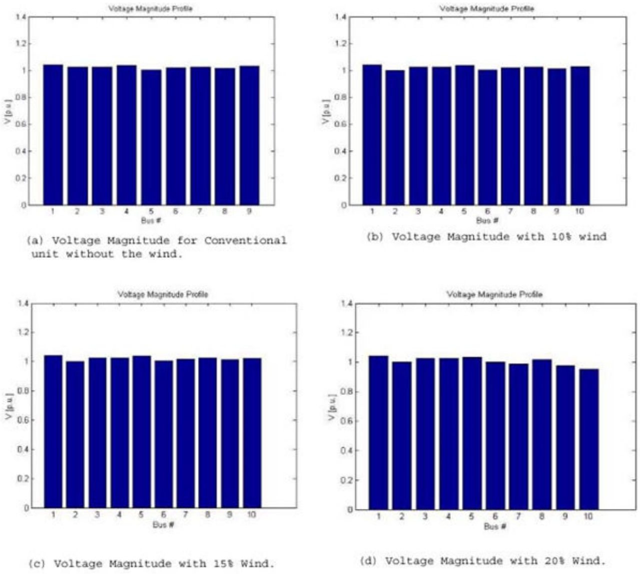

Fig. 2 Voltage profile (a) no wind, (b) 10% wind (c) 15% wind and (d) 20% wind penetrations

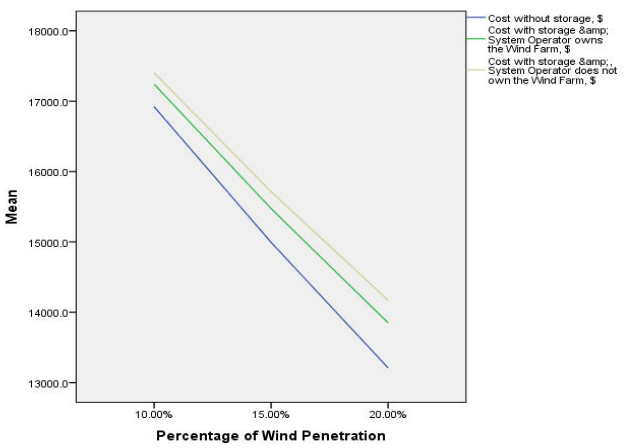

Fig. 3 Plot of cost for varying level of wind penetrations

V. Conclusion

The paper investigated wind farm participation in the energy market using a production cost study in IEEE 9 bus system. As the wind penetration levels increases the high variability in wind generation causes stability issues when there is no standby reserve. This increases the need for storage and cycling in conventional generation plants for a stable operation. The cost plummets as the percentage of the wind penetration increases. This is true under the assumption that the reserve is a battery bank reserve and no other spinning reserves are utilized and does not consider the installation cost of any reserves. This overall cost reduction is true for the operation and maintenance cost without considering the initial investment like land acquisition, installations and other preliminary cost related to establishing a business.

VI. Appendix

Appendix 1

TABLE II
GENERATOR CHARACTERISTICS

Generator Characteristics	P (MW)	Pmax (MW)	Pmin (MW)	Q (Mvar)	Qmax (Mvar)	Qmin (Mvar)
Conventional Gen 1	71.63	450	0	27.9	9900	-9900
Conventional Gen 2	163	240	0	4.9	9900	-9900
Conventional Gen 3	85	90	0	-11.45	9900	-9900
Wind Gen 4	123	-	-	-	-	-
Reserve Gen 5	-	-	-	-	-	-

Note: Capacity factor for all generators is 75%.
Load =315MW
Wind Output power= 123MW (Stateline Wind farm in the state of Oregon)

Appendix 2

TABLE III
WIND TURBINE CHARACTERISTICS

No. of Vestas V-47 turbines	Output voltage of a unit	Output Power of a unit
399 units	690V	660kW

Appendix 3

TABLE IV
WIND FARM COST WITH NATURAL GAS BALANCING

Wind farm with Natural Gas Balancing	$/MW
Base	93
Balancing with NG	17
Extra Gas Back Up	6
Transmission Costs	27
Installation Costs	1,700,000
Total	1,700,143
Total Amount for 320MW generation plant	544,045,760

TABLE V
WIND FARM COST WITH COAL BALANCING

Wind farm with Coal Balancing	$/MW
Base	93
Balancing with Coal	55
Extra Gas Back Up	9
Transmission Costs	27
Installation Costs	1,700,000
Total	1,700,184
Total Amount for 320MW generation plant	544,058,880

Appendix 4

TABLE VI
PSAT PARAMETERS FOR WIND TURBINE

Power, Voltage and Frequency Ratings [MVA, kV, Hz]	[100 67 60]
Stator Resistance Rs and Reactance Xs [p.u. p.u.]	[0.01 0.01]
Rotor Resistance Rr and Reactance Xr [p.u. p.u.]	[0.01 0.08]
Magnetization Reactance Xm [p.u.]	3.00
Inertia Constant Hm [kWs/kVA]	3.00
Pitch control gain and time constant kp, Tp [p.u. s]	[10 3]
Voltage Control gain Kv [p.u.]	10
Power Control time constant Te [s]	0.01
Number of poles p and gear box ratio [int -]	[4 1/89]
Blade length and number [m,int]	[23.5 3]
Pmax and Pmin [p.u. p.u.]	[1.00 0.00]
Qmax and Qmin [p.u. p.u.]	[0.7 -0.7]
Number of wind generators that compose the park [10% 15% 20%]	[49 73 97]

REFERENCES

[1] Yuri Makarov, Shuai Lu, Bart Mcmanus, and John Pease. The future impact of wind on BPA power system ancillary services. In Transmission and Distribution Conference and Exposition. IEEE/PES, IEEE/PES, April 2008.
[2] Wiser, Ryan, Mark Bolinger, June 2011: 2010 Wind Technologies Market Report. Department of Energy. (Available online at http://www.windpoweringamerica.gov/pdfs/2010_annual_wind_ market_ report.pdf)
[3] Das, Trishna, 2013: Performance and economic evaluation of storage technologies, PhD dissertation, Iowa State University, 237 pp. (Available online at http://lib.dr.iastate.edu/etd/13047)
[4] John Hetzer, David C. Yu, and Kalu Bhattarai. An economic dispatch model incorporating wind power. IEEE Transactions on Energy Conversion, 23(2):603–611, June 2008
[5] Sorotomme, E., Ali Al-Awami, M. El-Sharkawi, April 2010: Multi Objective Optimization for Wind Energy Integration.Available online at: http://sgpubs.ieee.org/publications/latest-ieee-xplore-publications/plug-in-hybrid-electric-vehicle/961-multi-objective-optimization-for-wind-energy-integration
[6] Post, Willem, November 2013: A More Realistic Cost of Wind Energy. The Energy Collective. (Available online at http://theenergycollective.com/willem-post/310631/more-realistic-cost-wind-energy)
[7] F. Milano. (2002) PSAT, Matlab-Based Power System Analysis Toolbox. (Online) Available at: http://thunderbox.uwaterloo.ca/~fmilano
[8] Freris, L. and D. Infield (2008). Renewable Energy in Power Systems, Wiley.
[9] Y. Makarov, B. Yang, J. G. DeSteese, S. Lu, C. H. Miller, P. Nyeng, J.Ma, D. J. Hammerstrom, and V. V. Viswanathan, "Wide-Area Energy Storage and Management System to Balance Intermittent Resources in the Bonneville Power Administration and California ISO Control Areas," Pacific Northwest National Laboratory, Richland, WA, Tech.Rep….. June 2008.
[10] Gurobi Optimization (Online). Available: http://www.gurobi.com/
[11] DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA-Abbas A. Akhil, Georgianne Huff, Aileen B. Currier, Benjamin C. Kaun, Dan M. Rastler, Stella Bingqing Chen, Andrew L. Cotter, Dale T. Bradshaw, and William D. Gauntlett

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