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Title	Transmission connected wind curtailment with increasing wind capacity connection
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Publication date	2009-07
Publication information	Burke, Daniel J., and Mark O'Malley. "Transmission Connected Wind Curtailment with Increasing Wind Capacity Connection." IEEE, 2009.
Conference details	Paper presented at IEEE Power & Energy Society General Meeting, July 26-30, 2009, Calgary, Canada
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/3339
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Publisher's version (DOI)	10.1109/PES.2009.5275377

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Transmission Connected Wind Curtailment With Increasing Wind Capacity Connection

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Abstract— Many countries have ambitious plans to increase wind energy penetration levels in the near future. With a low capacity factor and even lower capacity credit, wind power is a fundamentally different power generation source than conventional plant. Traditional planning methodologies focusing solely on the impact of turbine capacity's impact on line flow worst-case scenarios may unnecessarily impede cost-effective wind integration. This paper assesses the impact of increased wind capacity connection on wind energy curtailment indices using a security-constrained optimal power flow model. Results indicate significant scope for increased wind capacity connection exists if small levels of wind energy curtailment are accepted.

Index Terms—power system planning, power system security, power transmission, wind energy.

I. INTRODUCTION

Wind power is expected to make a significant contribution in future to countering the environmental and energy security challenges presently facing many countries around the world [1-4]. Increasing the wind energy penetration level is often impeded by the lack of transmission capacity in the areas where the most advantageous wind resources are available. In some cases delays associated with transmission system expansion may also be compounded by low public tolerance of such large scale over-head infrastructural developments [5]. Until this significant infrastructural roll-out is completed on the ground, then innovative power system planning, operation and policy methods may be required to accelerate the wind connection process in the meantime. Previous work has proposed the optimal allocation of 'firm' wind capacity to separate transmission buses with the aim of maximising the potential of the existing transmission system [6]. Transmission access for new generation has been traditionally assessed on the basis of maintaining secure power system operation using deterministic 'snapshot' analyses at assumed worst-case scenarios such as the maximum peak and/or minimum

customer loading scenario [7]. To cater for the fluctuating and interdependent nature of wind power output at distinct geographical sites the methods of [6] used a more extensive year-long multivariate time series approach with a novel model reduction scheme to allocate 'firm' wind capacity by correctly identifying the worst case line flow scenarios regardless of when or under what system loading conditions they occurred.

Probabilistic load flow has been proposed to study the statistical distributions of line flow and bus voltage behaviour. The impact of wind power on transmission system performance has been studied using such methods in [8-9]. Knowledge of the probability density function of line power flow allows the system designer to estimate the probability of line overload prior or subsequent to contingency conditions for example. Extreme or worst-case power flow scenarios by definition typically have a low probability of occurrence. Furthermore, wind power is a low capacity factor source of generation, and has an even lower load-carrying capability or capacity credit given its non-dispatchable nature [10]. The well-documented [11] low contribution of wind capacity to power system overload probability over an extended time-frame must be considered when assessing the feasibility of increased wind capacity connection. Power system planning analyses that focus primarily on the supply of wind energy at times of lower network congestion rather than the contribution of wind capacity to worst-case-scenarios will give a much more realistic representation of the overall transmission system's wind capacity connection capability. Such a generation network access philosophy is more aligned with the true policy goals of [1] – increased wind capacity connection is simply a manifestation of the need to integrate wind energy.

Significantly greater wind capacity connection feasibility for a defined level of wind energy curtailment on the Greek power system was reported in [12]. The methods of [12] assumed an equal contribution of each wind farm to the network overload and thus re-dispatched the wind plants on an equal basis however. Re-dispatch of conventional plant was not considered either. This paper applies a security constrained optimal power flow (SCOPF) approach to provide a secure generation dispatch – the wind energy curtailment process is thus more consistent with respect to normal power system operational procedure. Preliminary results suggest that significantly more wind capacity may be connected to a given network if a small amount of curtailment is allowed, and that some network positions have much greater scope for wind energy connection than others.

This work was conducted in the Electricity Research Centre, University College Dublin, Ireland, which is supported by Airtricity, Bord na Mona, Cylon Controls, the Commission for Energy Regulation, Eirgrid, ESB Networks, ESB Powergen, Siemens, South-Western Services and Viridian. The work of D. J. Burke was supported by Sustainable Energy Ireland through a postgraduate research scholarship from the Irish Research Council for Science Engineering and Technology.

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II. WIND CURTAILMENT ASSESSMENT

Optimal power flow can be used to determine the least cost system dispatch solution to serve a known customer load, with defined generation costs and a network model with given line capacity limits. Dispatch with respect to 'N-1' security constraints is typically applied in most power systems, such that network overloads or system load imbalance will not result subsequent to any first-contingency scenarios that may occur [13]. As such the SCOPF solution is a pre-emptive re-dispatch that assumes each possible contingency could occur, even if most of the time the system remains in an intact state for the subsequent period of interest.

A DC load flow SCOPF model with respect to 'N-1' line contingencies is applied in this paper. System load and wind time series profiles are assumed known. For a particular potential wind farm location the total wind turbine capacity is increased in discrete steps (by appropriately scaling the wind farm's individual power output time series) and a unit commitment is carried out to determine which conventional units should be online for that particular time period with that particular load and wind output level. Knowing which units are online at each hour, a year-long SCOPF dispatch model of hourly resolution is carried out. The results of the SCOPF model can be compared to a year-long economic dispatch model of the same resolution that does not account for network security limits. As wind is assumed to have priority dispatch, its total energy production in the economic dispatch model will be given by its capacity factor. Any discrepancy between the wind dispatched in the SCOPF model and the economic dispatch model is a result of transmission network limitations. The amount of wind capacity where network overload begins to occur can be related to that which would be attributed a 'firm' capacity connection offer based on the traditional worst-case-scenario planning philosophy. Studying the increase in yearly wind energy curtailment with respect to the added wind capacity gives an indication of the networks' wind energy harvesting potential in that area. A flowchart of the year-long study as applied in this paper is given in Fig.1 below.

Fig.1. Assessing the wind energy capability of a transmission area

III. TEST-SYSTEM

The simple 35-bus, 54-line test system used to study the effect of increased wind capacity on wind energy curtailment indices is illustrated in Fig.2 below. The network parameters are based on a simplified representation of the Irish All-Island 220/275/400 KV transmission network, combined with generator parameters from a small subset of the existing All-Island generation portfolio. Details of the conventional plant, assumed fuel input costs, the maximum load values at each bus, as well as the line reactance parameters and assumed active power flow capacity limits are contained in the Appendix section. The total conventional generation capacity was 2256.1 MW. Historical load time series data was used from the Irish power system. The peak system load for the test system was 1825.2 MW. The average load was 1246.6 MW.

Wind capacity was increased in 10 MW increments from zero to 200 MW of total capacity at 4 distinct transmission positions at buses 12, 14, 27 and 30 (for each bus position's analysis, the capacity of each other farm was assumed zero). The same wind power output time series, recorded from an actual wind farm on the Irish power system, was applied to each bus position for consistency. The unit commitment stage (without a network model included) was carried out using the commercial software tool Plexos, version 4.907 [14], while the economic dispatch and SCOPF stages were implemented in the MATLAB software environment [15] with linear incremental energy costs assumed to model conventional plant operation. The 'linprog' function optimisation solver in MATLAB was applied to the optimal dispatch problem. Wind power output was assumed have priority dispatch status, with a zero incremental cost. The operational energy cost was minimized at each hour - market operation or transmission constraint payments were thus not included in the cost function.

Fig.2. The test system transmission network schematic.

IV. RESULTS

The wind energy curtailment levels for each wind farm location with 10 MW wind capacity increments are presented in Table I and illustrated in Fig.3. The resulting load flow from the unconstrained economic dispatch model and the SCOPF dispatch model (prior to and post-contingency) for the line from bus 6 to bus 12 under all possible line flow contingencies is illustrated in Fig.4 for 200MW of wind capacity connected at bus 12. Fig.4 illustrates how the load flow in the SCOPF model is truncated at the line capacity level of 70 MW, resulting in power output curtailment for the wind farm at bus 12.

TABLE I
WIND ENERGY CURTAILMENT (%) AT DISTINCT TRANSMISSION LOCATIONS
WITH RESPECT TO INCREASING WIND FARM CAPACITY

Wind Capacity	Wind Capacity Bus Location			
	12	14	27	30
10	0	0	0	0
20	0	0	0	0
30	0	0	0	0
40	0	0	0	0
50	0	0	0	0
60	0	0 *	0	0
70	0	0.010361	0	0
80	0 *	0.205	0.14303 *	0
90	0	0.70	0.2136	0 *
100	0.0000241	1.79	0.30377	0
110	0.0463	3.007	0.3958	0
120	0.574	4.41	0.495	0
130	1.92	6.0171	2.0432	0
140	3.96	7.5681	2.2937	0.00737
150	6.391	10.6693	2.541	0.10768
160	8.813	12.23	2.7985	0.53732
170	11.236	13.7744	3.0562	1.4067
180	13.616	15.2739	4.9363	2.6608
190	15.943	16.6973	5.24	4.2158
200	18.66	19.364	5.5484	5.9357

Fig.3. Wind energy curtailment with respect to increasing wind capacity addition at distinct network locations.

Fig.4. Power flows in branch from bus 6 to bus 12 for 200 MW of wind connection at bus 12 with all 'N-1' transmission line contingencies.

The asterisk in each column of Table I denotes the wind capacity connection level at which the unconstrained economic dispatch load flow violated a security constraint. For buses 12 and 14 wind curtailment does not begin to occur at this level however, as often the SCOPF model will re-dispatch conventional plant instead of wind to minimise the operational costs. This is especially true for bus 30, where the wind farm is located at the same network position as a costly open-cycle gas turbine (OCGT) plant, which may be curtailed instead.

V. DISCUSSION

The wind energy curtailment results indicate that the point at which wind curtailment begins (traditionally associated with the concept of a 'firm' connection offer) is a poor representation of the overall wind capacity connection potential of each transmission location. Significantly more wind capacity may be connected to a given transmission system location if only a small percentage of energy curtailment is accepted, with no significant rise in congestion costs and little impact on power system reliability. This can be attributed to the relative skew-ness of the probabilistic load flow probability distribution, the low coincidence of typical wind power generation behaviour with such extreme power flow conditions, and the relative cost of curtailing wind with zero marginal cost in place of conventional plant with higher incremental cost. A power system's transmission network and the planning methodologies used to accommodate wind upon it should therefore be viewed as the means to harvest wind energy rather than simply to facilitate the connection of wind capacity. The results of Table I also highlight the difference in wind energy harvesting potential at different network locations. While both bus 14 and bus 27 have similar capability to connect wind capacity before curtailment begins

to occur, there is significantly less wind energy curtailment per MW of capacity added at bus 27 subsequent to this (see the relative slopes in Fig.3). This is important to consider, as an economically viable wind project may be able to accept no more than a certain small percentage of energy curtailment.

The results presented in this paper are based on a DC load flow model – reactive power flows and bus voltage limits are not included. Furthermore, only one year of wind data is applied to the SCOPF model – significant variation in wind power output, and/or its coincidence with peak customer load, can occur from one year to the next. Each network location was considered separately for an increase in wind capacity – if multiple wind projects are considered together then their statistical interdependence and/or common location in the transmission network could have a significant positive or negative impact on their respective energy curtailment indices. This paper considers wind curtailment for transmission network congestion reasons – wind curtailment for unit commitment or load balancing reasons may also be required for very high wind penetration and its associated increase in variability and uncertainty. This would likely increase the overall wind energy curtailment for each wind farm, again with obvious consequences for their economic viability. While the results presented in this paper are thus of an approximate nature only, the principle highlighted is likely to apply in practice for a more detailed SCOPF model also.

VI. CONCLUSION

This paper presents the results of wind energy curtailment with increasing wind capacity connection to a simple test transmission system network. Significantly more wind capacity may be potentially connected to a given transmission system if even a small amount of wind energy curtailment is allowed. Different transmission system areas may also have greater wind energy harvesting potential than others, even if they begin to incur curtailment at the same capacity connection level. Transmission system access methodologies and policy for wind connection should therefore be modified appropriately to reflect this principle – the low occurrence of transmission congestion and associated re-dispatch costs may be greatly outweighed by the benefit of accelerating the connection of environmentally friendly and cost-predictable wind energy.

VII. APPENDIX

TABLE A-I
BRANCH REACTANCE PARAMETERS AND CAPACITY LIMITS

FROM BUS	TO BUS	X _L (100 MVA BASE)	LIMIT (MW)	FROM BUS	TO BUS	X _L (100 MVA BASE)	LIMIT (MW)
1	2	0.02	400	18	21	0.044	150
1	3	0.02	400	19	20	0.01	160
2	3	0.011	400	19	22	0.01	320
3	4	0.039	250	20	21	0.01	300
3	5	0.075	225	20	22	0.01	320
3	10	0.073	300	21	24	0.02	280
4	7	0.084	200	21	26	0.038	410
5	6	0.02	280	22	23	0.003	500
6	11	0.06	170	23	24	0.008	500
6	12	0.076	70	24	27	0.053	440
7	8	0.007	400	25	27	0.095	210
7	10	0.061	220	25	29	0.025	450
8	9	0.042	380	26	27	0.03	330
8	15	0.077	270	27	28	0.025	440
9	13	0.023	430	28	29	0.011	180
9	17	0.079	350	28	31	0.0185	150
10	16	0.08	175	28	34	0.036	100
11	17	0.051	175	29	30	0.011	80
12	19	0.046	175	29	33	0.0135	130
13	14	0.04	250	29	35	0.0282	100
13	24	0.046	380	30	33	0.02	80
14	15	0.029	240	31	32	0.005	110
15	25	0.076	285	31	34	0.0294	110
16	21	0.094	220	31	35	0.02	130
17	18	0.022	160	32	35	0.0196	130
17	19	0.036	210	33	34	0.0065	90
17	21	0.016	330	33	35	0.0198	100

TABLE A-II
MAXIMUM BUS LOAD VALUES

Bus	Load (MW)	Bus	Load (MW)
1	59.37	19	117.86
2	2.62	20	117.28
3	75.96	21	77.41
4	20.66	22	191.784
5	74.5	23	20.37
6	9.57	24	0
7	37.25	25	82.07
8	0	26	75.96
9	25.03	27	74.21
10	64.32	28	98.95
11	29.48	29	34.92
12	48.89	30	86.72
13	5.093	31	75.37
14	0	32	58.20
15	91.09	33	42.20
16	63.73	34	0
17	17.46	35	46.86
18	0		

TABLE A-III
FUEL COSTS APPLIED TO DISPATCH MODEL

FUEL	COST (EURO/GJ)
COAL	2.2
GAS	6.25
PEAT	3.0
OIL	5.35

TABLE A-IV
CONVENTIONAL PLANT INFORMATION

Bus Number	Plant Description	
	Capacity (MW)	Fuel
2	3*95	Gas (OCGT)
9	2*286	Coal
10	1*83	Gas(CHP)
17	1* 90, 1*117.6	Peat
22	3*109.5	Oil
23	1*400	Gas (CCGT)
30	2*95	Gas (OCGT)
35	2*95	Gas (OCGT)

VIII. ACKNOWLEDGMENT

The authors thank the Irish TSO Eirgrid, for their timely co-operation and assistance in the supply of time series data.

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