FEASIBILITY STUDY OF WIND TURBINE STARTUP SPEED WITH DEAD BAND

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Abstract. Wind turbines are usually designed and operated with fix startup speed. It could startup and shutdown repeatedly when the wind fluctuates around the startup speed. The excessive stress induced by frequent startup and shutdown could enhance likelihood of component failure and negatively impact the availability of a wind turbine. The startup speed with dead band is proposed in this article to prevent from frequent startup. 5-year wind data of 15 wind farms are analyzed to evaluate the reduction in the times of startup and potential loss of wind power production using the proposed approach. Numerical simulation suggests that the times of startup could be reduced by half with trivial reduction in potential wind power generation in most of investigated sites once an appropriate dead band is adopted
Keywords: *wind power; times of startup; mean wind speed; consecutive shutdowns; loss in power production*

Introduction

Wind turbines are hard-to-access structures usually located in remote areas. The wind turbine is a unique power generating system because power train components are subject to highly irregular loading from turbulent wind conditions (Walford, 2006). They are exposed to the risk of component failure due to the extreme and the average wind regimes (Ribrant and Bertling, 2007). The component failure could cause excess maintenance costs and reduce the power generation. It is speculated that the maintenance cost may account for 10% to 30% of the total income of wind turbines (Walford, 2006; Ribrant and Bertling, 2007).

Wind turbines operate in the presence of large uncertainties. Many outliers are likely to be generated, particularly during transient operations such as startup and shutdown (Yampikulsakul et al., 2014). For example, frequent operation of circuit breaker during off-grid and grid connection could result in malfunction of circuit breakers notably.

Wind turbines are designed with specific startup speed. Since whether the startup speed could be adjusted are not mentioned in any operation guideline of wind turbine, wind turbines are usually operated with fixed startup speed according to authors' knowledge. Therefore, it could shut down and startup repeatedly when the wind speed fluctuates around its startup speed. The excessive stress and operation of circuit breakers induced by frequent startup and shutdown could enhance likelihood of component failure of a wind turbine.

Startup speed with a dead band is proposed in this article to reduce the times of startup. The paper is organized as follows. The concept of startup speed with dead band is introduced in Section II. The wind data utilized for numerical simulation is analyzed in Section III. The feasibility of startup speed with dead band is analyzed in Section IV. Numerical simulation is given in Section V to evaluate performance of startup speed with dead band. Section VI concludes the article.

Startup speed with dead band

Dead band, an interval of a band where no action occurs, is widely used in controlling applications to prevent oscillation or repeated activation-deactivation cycles. The startup speed with dead band can be described as *Fig.1*.

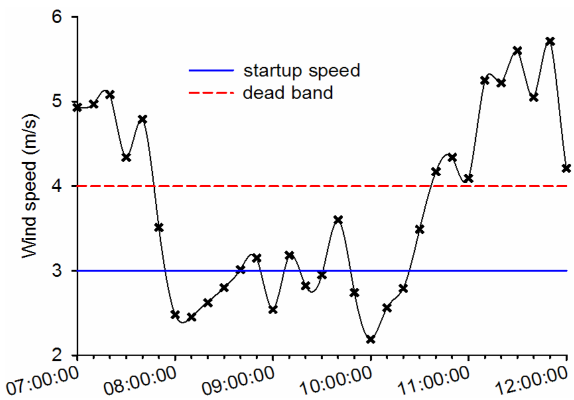

Figure 1. *Description of startup speed with dead band*

It can be observed that a wind turbine with startup speed of 3.0 m/s could startup 4 times from 7:00 to 12:00. It is feasible to add a dead band with lower and upper boundaries of 3.0 m/s and 4.0 m/s as shown in *Fig.1*. That is, the wind turbine startup when the wind speed is higher than 4.0 m/s and shutdown when the wind speed is lower than 3.0 m/s. Thereafter, the times of startup could be reduced to 1 as shown in *Fig.1*. Moreover, since wind power is proportional to the cube of wind speed, it is speculated that the slight reduction in wind power generation caused by the dead band could be covered by the potential benefit arise from reduction in times of startup related wear and enhanced availability.

Wind data

5 years (from Sept. 2, 2003 to Aug. 31, 2008) 10-minute synthetic wind data at a hub height of 85m of 15 actual or proposed wind farms in new Zealand (Turner et al., 2009) are investigated in the article. The geographical locations of investigated sites are shown as *Fig.2*. Of which, STH is the regional identifier for southland and Otago, CTY for Canterbury, CKS for Cook strait, MWT for Manawatu and Wanganui, CNI for Central North Island and Hawkes Bay, and NTH coastal parts of Waikato, Auckland, Coromandel, and Northland (Turner et al., 2009).

Since wind turbines startup and shutdown repeatedly when wind fluctuate around the startup speed, it is speculated that the times of startup could be higher in the sites with lower wind speed than that of sites with higher wind speed. In order to find out whether

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this holds true, the data are analyzed as follows. The times of wind speed surplus and lower than startup speed is counted as times of wind turbine startup and shutdown due to fluctuation of wind speed. The mean wind speed and the times of startup of investigated sites are listed ascending by times of startup as *Table 1*.

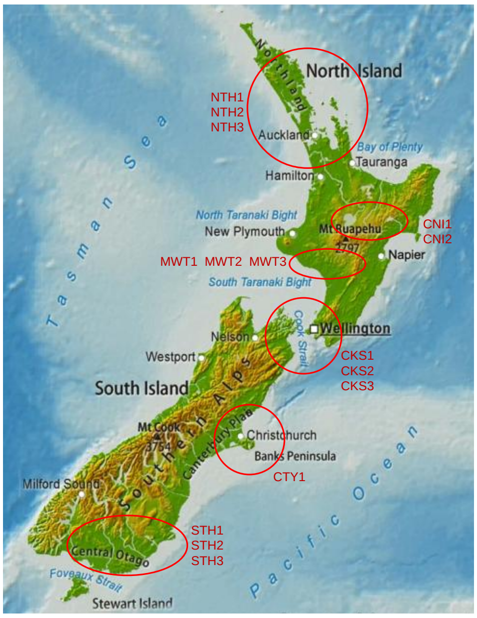

Figure 2. *Geographical location of investigated sites*

Table 1. *Times of startup and mean wind speed in investigated stations*

Station	Times of startup	Mean wind
CKS2	2203	10.89
MWT1	2209	10.53
NTH2	**2305**	**8.33**
MWT3	2324	9.57
CKS3	2327	11.3
NTH3	**2404**	**8.73**
STH3	2475	11.41
MWT2	2762	9.91
NTH1	**2858**	**8.45**
STH2	2996	9.56
CNI2	3010	8.49
CKS1	3437	9.10
CNI1	3637	9.15
CTY1	3890	8.28
STH1	4763	10.08

It can be observed that the time of startup varies notably from sites to sites. The time of startup ranges from 2203 to 4763 and the mean wind speed ranges from 8.28 m/s to 11.41 m/s. However, there is no obvious relation between the mean wind speed and the times of startup. For example, the STH1 with a higher mean wind speed of 10.08 m/s has the highest times of startup of 4763. On the contrary, NTH1, NTH2, and NTH3 with lower mean wind speed have the lower times of startup, too.

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Since the local topography has a notable impact on the regional wind characteristics (National Renewable Energy Laboratory, 1997; Ashcroft, 1994), it is speculated that the topography could play an important role in the times of startup. The sites over the open sea and flat terrain tend to have stable wind condition. Therefore, the fluctuation in wind speed and the times of startup and shutdown of wind turbines could be lower. On the contrary, the sites over complex terrain with larger roughness tend to have higher turbulence and gust. The wind turbines could startup and shutdown more frequently under such unstable wind condition.

According to geographic map of New Zealand as shown in *Fig.2*, the sites NTH1, NTH2, and NTH3 locate in open plain with flat terrain. Therefore, both the times of startup and mean wind speed in these sites are lower than that of other sites. Moreover, STH1, the site with highest times of startup, has a mean wind speed of 10.08 m/s, which is higher than majority of investigated sites. However, since accurate geographic location information of these sites is not accessible, we cannot identify the accurate factors that determine times of startup in a wind farm with investigated data.

Feasibility of startup speed with dead band

The dead band has gotten extensive application in control engineering, such as pitch and yaw control of wind turbine (Anthonis et al., 2007, Wu et al., 2012), tap change of transformer (Choi et al., 2009), etc. Usually, the purpose is to prevent oscillation or repeated activation-deactivation cycles and avoid unnecessary control.

Undoubtedly, unnecessary startup and shutdown of wind turbine could be prevented by dead band at large. However, it should be pointed out that the reduction in times of startup and shutdown of wind turbine is achieved at the cost of reduction in wind power generation, which should be evaluated too.

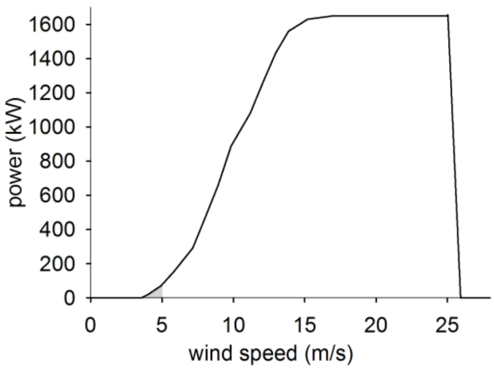

Figure 3. *Wind power curve of Vestas 66-1650*

The Vestas 66-1650 turbine (Power curve of Vestas, 2008) with a startup speed of 3.0 m/s is utilized in this study. The wind power curve is plotted as *Fig.3*. Since wind power that can be exploited is proportional to the cube of wind speed, the power production is rather low below 5.0 m/s as shown in shaded area of wind power curve. Therefore, it seems reasonable to establish a dead band below 5.0 m/s to avoid unnecessary startup and shutdown at the cost of slight reduction in wind power generation.

The potential effect of dead band should be evaluated. Since wind is caused by differences in atmospheric pressure, it is widely accepted that there is inherent temporal

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continuity in the wind speed (National Renewable Energy Laboratory, 1997). Therefore, it is reasonable to speculate that once the wind speed fluctuates over startup speed, the likelihood that a wind turbine to shutdown in the following time span is high. The intervals between consecutive startup and shutdown are calculated and their cumulative distribution functions are plotted as *Fig.4*.

The horizontal plot denotes interval between consecutive startup and shutdowns. The vertical plot denotes the likelihood of wind lower than startup speed (3.0 m/s in this article) within given time span.

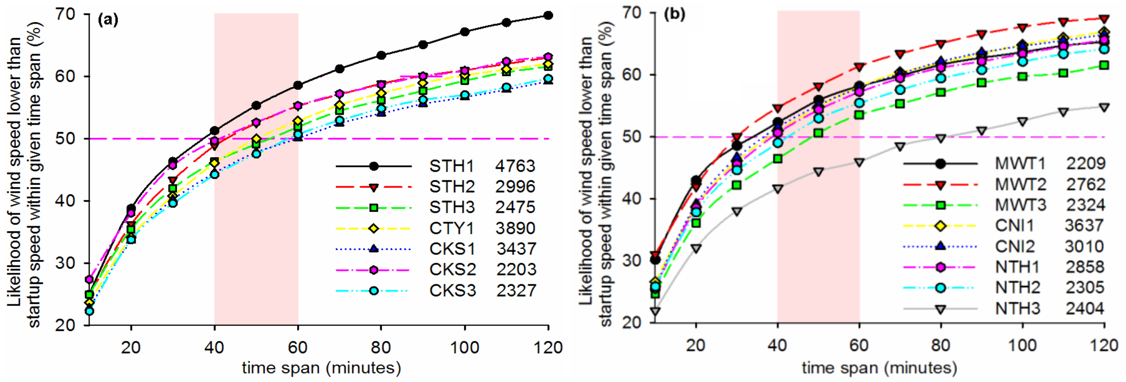

Figure 4. *CDF of intervals between consecutive shutdowns*

It can be observed from *Fig.4* that once a Vestas 66-1650 turbine startup, the likelihood that it re-shutdown within 10 minutes is around 20% to 30% in all investigated sites. The likelihood that it re-shutdown within 40 to 60 minutes is over 50% in most of investigated sites as shown in shaded area of *Fig.4*. Therefore, unnecessary startup and shutdown could be prevented substantially once appropriate approach is adopted.

It should be pointed out that the curve of NTH3 escalates much slower than that of other sites. When wind turbine startup, the likelihood that it shut down within 80 minutes is around 50% in the NTH3, which is 20 min more than that of other sites. The difference might be attributed to the stable wind condition over open terrain of the site.

Numerical simulation

Reduction in the times of startup

Appropriate configuration of dead band plays a key role to the reduction of times of startup. Startup speed of Vestas 66-1650, 3.0 m/s, is used as lower boundary of dead band. 3.1 m/s, 3.2 m/s to 5.0 m/s with a step of 0.1 m/s are used as upper boundary of the dead band. The times of startup associate with various upper boundaries are calculated with wind data and plotted as *Fig.5*. The detailed information is listed as *Table 2*.

- It can be observed there are unambiguous decline trends in all sites. The times of startup decline notably with higher upper boundary adopted.
- The decline ratio of times of startup fall off with higher upper boundary adopted. The decline ratio with an upper boundary over 4.0 m/s is notably milder as compared to those below 4.0 m/s in all sites.

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- The decline ratios of majority of sites with less times of startup, such as CKS3 (2327), NTH3 (2404), STH3 (2475), and MWT3 (2324), are milder than that of other sites. The times of startup with an upper boundary of 4.0 m/s in these sites are 68%, 55%, 53%, and 56% of original times of startup. It is speculated that the mild declining could be caused by the stable wind condition of these sites.
- The times of startup in majority of stations, except CKS1and above 4 sites, decline to below 50% of original number with an upper boundary of 4.0 m/s.
- The largest reduction (2176) occurs in STH1 while the smallest reduction (729) occurs in CKS3.

Table 2. *Time of startup in stations with various upper boundaries of dead band*

boundary (m/s)	STH1	STH2	STH3	CTY1	CKS1	CKS2	CKS3	MWT1	MWT2	MWT3	CNI1	CNI2	NTH1	NTH2	NTH3
3.0	4763	2996	2475	3890	3437	2203	2327	2209	2762	2324	3637	3010	2858	2305	2404
3.1	4357	2730	2264	3492	3181	1950	2211	1966	2483	2152	3273	2687	2567	2069	2200
3.2	4055	2546	2117	3223	2996	1772	2123	1770	2254	2007	2996	2459	2334	1891	2028
3.3	3777	2358	1974	3003	2822	1636	2031	1609	2062	1881	2762	2235	2141	1731	1906
3.4	3532	2185	1838	2799	2659	1508	1960	1463	1874	1766	2536	2061	1973	1591	1789
3.5	3330	2050	1731	2607	2510	1380	1881	1359	1718	1662	2365	1925	1824	1476	1701
3.6	3128	1924	1625	2439	2399	1302	1818	1267	1581	1580	2206	1811	1703	1358	1601
3.7	2967	1818	1533	2295	2314	1237	1751	1197	1488	1513	2082	1680	1595	1269	1532
3.8	**2822**	1724	1457	2189	2209	1175	1691	1135	**1386**	1440	1956	1561	1509	**1186**	1463
3.9	2709	1644	1383	2081	2125	1116	1645	**1089**	1310	1374	1856	**1478**	**1433**	1113	1398
4.0	2587	1558	1332	1994	2044	**1067**	1598	1044	1246	1318	**1772**	1409	1368	1053	1329
4.1	2497	**1509**	1297	**1930**	2008	1040	1545	1010	1196	1275	1701	1357	1314	1024	1283
4.2	2394	1440	1267	1854	1938	996	1498	965	1150	1222	1638	1297	1248	983	1233
4.3	2301	1392	**1232**	1801	1874	952	1461	938	1103	**1174**	1574	1242	1189	953	**1189**
4.4	2221	1344	1189	1751	1826	918	1418	913	1055	1130	1514	1186	1134	929	1158
4.5	2140	1294	1165	1688	1774	878	1385	888	1010	1094	1451	1136	1092	907	1124
4.6	2051	1252	1130	1638	**1729**	853	1357	860	975	1060	1405	1084	1049	871	1098
4.7	1981	1222	1106	1590	1692	834	1323	830	933	1030	1367	1051	1012	844	1075
4.8	1903	1196	1079	1555	1659	818	1295	811	897	1001	1330	1020	977	821	1053
4.9	1840	1169	1060	1514	1625	809	1266	796	868	971	1288	990	956	794	1036
5.0	1777	1136	1035	1471	1592	794	1244	787	839	957	1249	961	932	772	1015

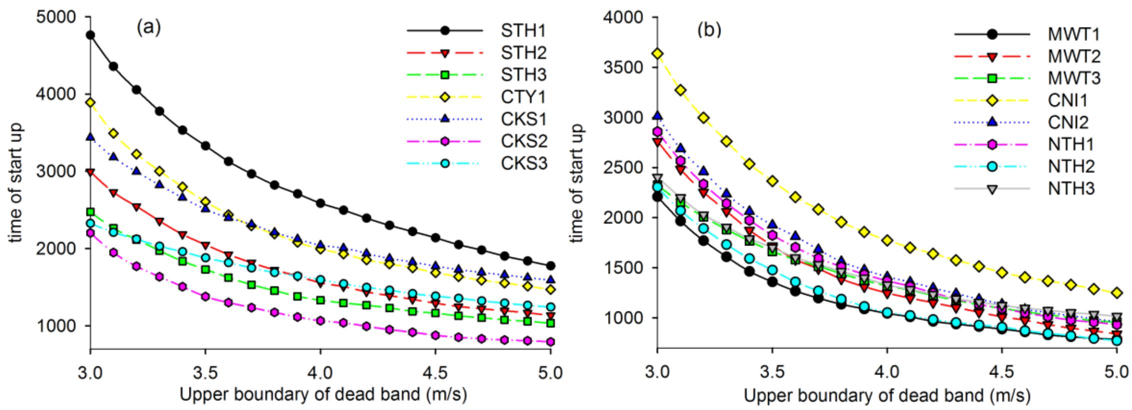

Figure 5. *Time of startup in stations with various dead band boundaries*

Reduction in the wind power generation

The times of startup is reduced at the cost of reduction in wind power generation. The reduction in potential wind power generation associate with various upper boundaries are calculated and plotted as *Fig.6*. The reduction below 4.0 m/s is enlarged and plotted in shaded area. The detailed information is listed as *Table 3*.

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- Since the cut-in speed of Vestas 66-1650 is 3.5 m/s, there is only trivial loss in wind power generation below the cut-in speed. Consequently, loss in wind power generation is slim with upper boundary of 3.5 m/s.
- It can be observed that the loss curves of wind power generation escalate slowly below 4.0 m/s. The loss in wind power generation range from 1545 kWh to 4308 kWh with upper boundary of 4.0 m/s during the whole 5 years.
- The loss in wind power generation escalates rapidly when upper boundary of dead band over 4.0 m/s adopted. The loss in wind power generation range from 17834 kWh to 48492 kWh with upper boundary of 5.0 m/s, which is 10 times higher than that of 4.0 m/s.

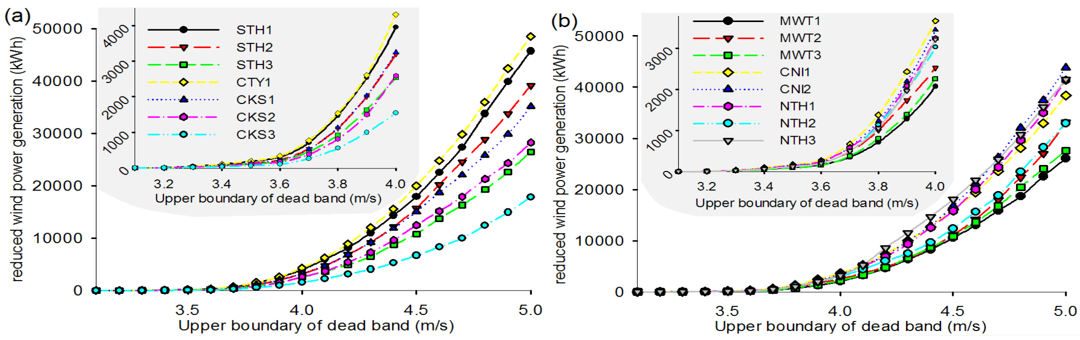

Figure 6. *Loss in wind power generation associated with various upper boundaries of dead band*

Table 3. *Loss in power production with various dead band boundaries*

boundary (m/s)	STH1	STH2	STH3	CTY1	CKS1	CKS2	CKS3	MWT1	MWT2	MWT3	CNI1	CNI2	NTH1	NTH2	NTH3
3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.2	8	5	5	8	5	4	2	4	6	4	7	6	6	4	4
3.3	42	27	23	41	29	22	13	23	29	20	36	34	33	26	24
3.4	100	68	61	106	71	54	33	58	70	48	94	80	79	65	60
3.5	180	131	110	195	131	101	61	98	132	91	171	150	145	123	117
3.6	303	222	187	335	213	165	99	165	216	151	275	239	244	210	195
3.7	699	536	457	770	518	380	264	349	481	374	669	598	581	503	498
3.8	1473	1110	919	1537	1133	811	553	713	1001	798	1376	1227	1138	1137	1053
3.9	2540	2007	1636	2607	2026	1495	992	1278	1725	1390	2425	2184	2082	1971	1967
4.0	3957	3194	2539	4309	3250	2589	1545	2066	2518	2254	3662	3439	3234	3023	3204
4.1	5950	4718	3657	6247	4766	3702	2269	3242	3650	3345	5277	5063	5005	4407	5231
4.2	8138	6871	4919	8921	6817	5391	3137	4597	4844	4738	7383	7204	6898	6020	8589
4.3	11020	9186	6459	12022	9212	7259	4041	6310	6462	6599	10029	9940	9386	7533	11569
4.4	14350	12208	8713	15594	11864	9605	5261	8256	8543	8675	12704	12964	12576	9672	14684
4.5	17930	15702	10786	19988	15056	12475	6690	10559	11131	10847	16069	16782	15841	12385	18091
4.6	22506	20216	13727	24761	18679	15161	8312	12977	14184	13647	19410	21140	20045	15626	21822
4.7	27316	24531	16296	29832	22062	17910	10005	15862	18017	16773	23605	26317	24370	18848	25925
4.8	33750	28854	19283	35932	25802	21272	12414	18671	22393	20440	28111	32071	29671	23465	30732
4.9	39888	33748	22622	42368	29836	24306	14921	22555	27029	24088	32983	37422	35020	28254	36146
5.0	45697	39154	26452	48492	35162	28212	17834	26052	33160	27578	38333	43832	41366	32931	41484

Selection of upper boundary of dead band

Since reduction in times of startup is achieved at the cost of loss of wind power generation, selection of boundary of dead band should be determined based on tradeoff between the potential benefit and the cost. The cost induced by reduction in wind power generation could be roughly evaluated with historical wind data. The benefit led by

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reduction in startup should be evaluated with enhanced reliability and availability. Since reliability and availability of wind turbines are determined by a series factors, it is not feasible to quantify the benefit led by reduction in startup & shutdown of wind turbines. Therefore, it is acceptable to select an affordable cost as the boundary of dead band for the potential benefit of uncertainty.

It can be observed from *Fig. 6* and *Table 3* that the loss in wind power generation range from 1545 kWh to 4308 kWh with a boundary of 4.0 m/s during the whole 5 years. The cost is $77.25 to $215.4 according to a power purchase agreement of $50/MWh. It is trivial as compared to reduction of times of startup & shutdown by half (ranging from 729 to 2176) in majority of sites. Therefore, 4.0 m/s could be an acceptable candidate for upper boundary of dead band.

Since the investigated sites are of diversified wind condition, ultimate selection of the dead band depends on wind condition of the sites. In order to provide an integrate knowledge of the cost and benefit of dead band, the loss in wind power generation is divided by the reduction in times of startup & shutdown and listed as *Table 4*. The data are plotted as *Fig.7*.

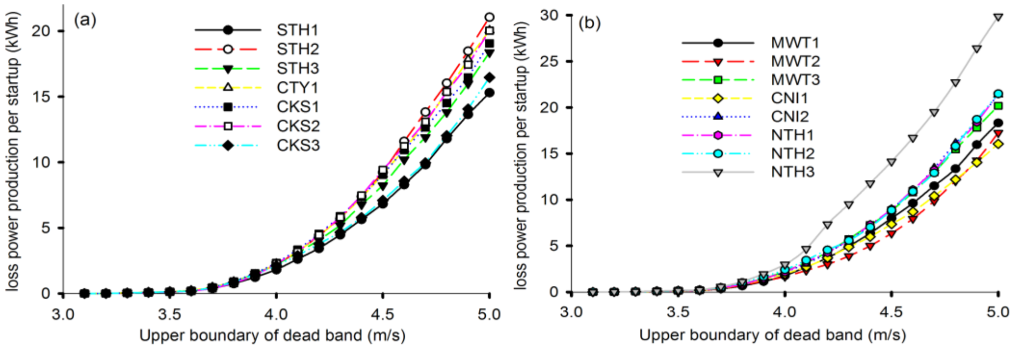

Figure 7. *Loss in wind power generation associated with various upper boundaries of dead band*

Table 4. *Loss in power production per reduction in time of startup*

	STH1	STH3	CTY1	CKS1	CKS2	CKS3	MWT1	MWT2	MWT3	CNI1	CNI2	NTH1	NTH2	NTH3
3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.2	0.011	0.014	0.012	0.011	0.009	0.010	0.009	0.012	0.013	0.011	0.011	0.012	0.010	0.011
3.3	0.043	0.046	0.046	0.047	0.039	0.044	0.038	0.041	0.045	0.041	0.044	0.046	0.045	0.048
3.4	0.081	0.096	0.097	0.091	0.078	0.090	0.078	0.079	0.086	0.085	0.084	0.089	0.091	0.098
3.5	0.126	0.148	0.152	0.141	0.123	0.137	0.115	0.126	0.137	0.134	0.138	0.140	0.148	0.166
3.6	0.185	0.220	0.231	0.205	0.183	0.195	0.175	0.183	0.203	0.192	0.199	0.211	0.222	0.243
3.7	0.389	0.485	0.483	0.461	0.393	0.458	0.345	0.377	0.462	0.430	0.450	0.460	0.486	0.571
3.8	0.759	0.903	0.904	0.923	0.789	0.870	0.664	0.728	0.903	0.819	0.847	0.844	1.016	1.119
3.9	1.237	1.498	1.441	1.544	1.375	1.455	1.141	1.188	1.463	1.362	1.426	1.461	1.654	1.955
4.0	1.818	2.221	2.273	2.333	2.279	2.119	1.773	1.661	2.241	1.964	2.148	2.171	2.415	2.981
4.1	2.626	3.104	3.187	3.335	3.183	2.902	2.704	2.331	3.189	2.726	3.063	3.242	3.440	4.666
4.2	3.435	4.072	4.382	4.548	4.466	3.784	3.695	3.005	4.300	3.693	4.206	4.285	4.554	7.335
4.3	4.476	5.196	5.755	5.894	5.803	4.666	4.965	3.895	5.738	4.861	5.622	5.624	5.572	9.522
4.4	5.645	6.775	7.290	7.364	7.475	5.788	6.370	5.005	7.266	5.984	7.108	7.295	7.029	11.785
4.5	6.836	8.234	9.077	9.054	9.415	7.102	7.993	6.353	8.819	7.351	8.955	8.970	8.859	14.134
4.6	8.299	10.206	10.995	10.936	11.230	8.569	9.620	7.937	10.797	8.696	10.976	11.081	10.897	16.709
4.7	9.819	11.904	12.970	12.643	13.083	9.9651	11.503	9.8507	12.962	10.399	13.434	13.202	12.901	19.507
4.8	11.801	13.813	15.388	14.512	15.359	12.029	13.356	12.007	15.450	12.185	16.116	15.774	15.812	22.748
4.9	13.646	15.987	17.832	16.466	17.436	14.063	15.963	14.271	17.803	14.041	18.526	18.412	18.699	26.423
5.0	15.304	18.369	20.046	19.058	20.023	16.467	18.321	17.244	20.174	16.052	21.392	21.478	21.481	29.866

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It can be observed that there is slim deviation in loss of power production per startup below 4.0 m/s since there is only trivial loss in wind power generation. Losses of power production per startup range between 1.6 kWh to 3.0 kWh with a boundary of 4.0 m/s. The reduction in power production per startup escalated rapidly over 4.0 m/s. Since the NTH3 is of the lowest times of startup (2404), escalation of the boundary will case less reduction in times of startup. Consequently, the reduction in power production per startup in NTH3 is much faster than that of other sites.

Interannual variation of wind condition

Since wind condition could have notable impact on the times of startup, the interannual variation of wind and its impact on uncertainty of effect of dead band are investigated in this section.

Table 5. *Annual mean wind speed of consecutive 5 years (m/s)*

Time span	STH1	STH2	STH3	CTY1	CKS1	CKS2	CKS3	MWT1	MWT2	MWT3	CNI1	CNI2	NTH1	NTH2	NTH3
03-04	10.37	9.70	11.23	8.56	9.31	11.48	11.72	10.75	10.01	9.78	9.44	8.56	8.42	8.41	8.84
04-05	10.22	9.79	11.52	8.03	8.88	10.82	11.17	10.76	9.970	9.62	9.12	8.83	8.50	8.24	8.74
05-06	9.76	9.18	10.99	8.03	8.85	10.49	10.99	10.28	9.77	9.35	8.92	8.29	8.27	8.18	8.44
06-07	10.46	10.21	12.24	8.61	9.27	11.05	11.46	10.82	10.44	9.59	9.31	8.76	8.60	8.36	8.72
07-08	9.58	8.92	11.09	8.17	9.20	10.61	11.17	10.02	9.39	9.52	8.97	7.99	8.47	8.47	8.90
mean wind	10.08	9.56	11.41	8.28	9.10	10.89	11.3	10.53	9.91	9.57	9.15	8.49	8.45	8.33	8.73
standard deviation	0.39	0.51	0.50	0.28	0.22	0.39	0.29	0.36	0.38	0.16	0.22	0.35	0.12	0.12	0.18
Coefficient of variation (%)	3.84	5.32	4.39	3.43	2.43	3.62	2.54	3.39	3.86	1.64	2.40	4.06	1.46	1.44	2.04

Table 6. *Annual times of startup of consecutive 5 years*

site	boundary (m/s)	03-04	04-05	05-06	06-07	07-08	site	boundary (m/s)	03-04	04-05	05-06	06-07	07-08	site	boundary (m/s)	03-04	04-05	05-06	06-07	07-08
STH1	3.0	828	894	1017	960	1015	CKS2	3.0	342	443	489	435	455	CNI1	3.0	708	659	747	716	770
	3.5	72%	72%	70%	69%	70%		3.5	66%	63%	62%	66%	63%		3.5	66%	66%	67%	67%	62%
	4.0	57%	56%	52%	54%	56%		4.0	53%	51%	46%	49%	49%		4.0	50%	50%	50%	47%	48%
STH2	3.0	559	543	650	523	691	CKS3	3.0	418	476	494	454	477	CNI2	3.0	635	499	591	534	715
	3.5	68%	70%	70%	69%	69%		3.5	82%	81%	82%	78%	83%		3.5	64%	63%	64%	66%	66%
	4.0	51%	52%	52%	54%	54%		4.0	70%	70%	70%	66%	69%		4.0	46%	46%	48%	49%	47%
STH3	3.0	462	434	522	464	553	MWT1	3.0	474	431	430	421	427	NTH1	3.0	566	576	565	518	595
	3.5	72%	68%	71%	72%	72%		3.5	57%	64%	63%	62%	66%		3.5	64%	65%	64%	68%	63%
	4.0	57%	54%	55%	54%	53%		4.0	43%	47%	50%	48%	52%		4.0	50%	47%	47%	53%	47%
CTY1	3.0	716	808	837	709	770	MWT2	3.0	558	564	460	528	614	NTH2	3.0	447	439	536	417	429
	3.5	69%	70%	67%	67%	66%		3.5	64%	62%	65%	63%	63%		3.5	68%	64%	67%	62%	64%
	4.0	52%	56%	52%	50%	49%		4.0	47%	43%	50%	45%	45%		4.0	46%	47%	46%	46%	48%
CKS1	3.0	606	699	780	656	663	MWT3	3.0	443	428	471	498	456	NTH3	3.0	452	446	553	498	437
	3.5	76%	75%	71%	76%	73%		3.5	73%	71%	74%	70%	74%		3.5	71%	72%	68%	73%	73%
	4.0	59%	62%	58%	61%	60%		4.0	56%	57%	57%	58%	59%		4.0	58%	55%	55%	53%	58%

The annual mean wind speed, its standard deviation, and coefficient of variation in each site of the consecutive 5 years from 2003 to 2008 are calculated and listed as *Table 5*. It can be observed that standard deviations in majority of sites (except STH2 and STH3) range between 0.12 to 0.40 and their coefficient of variation of annual mean

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wind speed ranges between 1.4% to 4.0%, which suggest there is moderate interannual variability in majority of sites.

In order to analyze the uncertainty in the effect of dead band under the context of interannual variability of wind conditions, annual times of startup without dead band are listed as *Table 6*. In order to provide with an explicit view, the annual times of startup with an upper boundary of 3.5 m/s and 4.0 m/s are divided by that without dead band and listed in *Table 6*, too.

It can be observed that there are rather small interannual variations in percentage of annual times of startup with dead band to that without dead band. The interannual variations in percentage of majority of sites are less than 5%, while the largest variation, 10%, occurs in MWT1 with boundary of 3.5 m/s (57% in 2003-2004 and 66% in 2007-2008) and 4.0 m/s (43% in 2003-2004 and 52% in 2007-2008). Therefore, it is speculated that the dead band determined based on historical data could achieve similar performance in reducing unnecessary startup in the coming days.

Conclusions

Startup speed with dead band is proposed in the article to prevent frequent startup & shutdown of wind turbines.

- Analysis of wind data of 15 actual and potential wind farms indicates that there is notable difference in the times of startup in different sits. The difference in times of startup is of no relation to the mean wind speed. It is speculated that the difference is caused by the local terrain related wind condition, such as turbulence.
- Numerical simulation suggests that the times of startup with an upper boundary of 4.0 m/s could be reduced to below 50% of original number in majority of sites. The reduction in times of startup ranges from 729 to 2176 in the investigated 5 years.
- The reduction in wind power generation ranges from 1545 kWh to 4308 kWh with upper boundary of 4.0 m/s during the whole 5 years. Although the benefit brought by reduction in times of startup cannot be quantified yet, the dead band of 4.0 m/s is acceptable since associated loss is trivial.
- Although there are moderate interannual variability in the wind condition, performance of dead band remains stable. Therefore, it is reasonable to determine an appropriate configuration of dead band based on statistical analysis of historical wind data.

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