OPTIMAL WIND POWER INTEGRATION CONSIDERING FLICKER EMISSION LEVELS; A CASE STUDY

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ABSTRACT

This paper mainly focuses on the challenge of interconnecting significant amounts of wind power into grids dominated by large number of wind power units. In this study, short term and long term flicker emission of wind turbines due to switching operation and in continues operation is estimated and evaluated with respect to the IEC 61000-3-7 standard. In this paper results from computer analyses of a simplified, yet realistic, radial distribution network with wind power integration, proposing possible solutions that enable safe operation of large wind farms are presented.

INTRODUCTION

Wind power has experienced rapid growth in the past decade. Regarding the rapidly increasing penetration rate of future wind farms in power systems, analysis of how interconnected wind farms affect power system operation becomes quite significant. One question that needs to be asked, however, is the impact of large amounts of wind power on distribution system.

To determine the maximum wind power that can be injected to the power grid, short circuit level on the considered bus should be investigated [1]. Once the total number of wind turbines regarding the nominal values is determined, the voltage quality and flicker effect of such system on distribution network is computed and might decrease the total number of wind turbines [2]. Flicker emission level limits total wind power. According to IEC 61000-3-7, flicker emission levels for short term and long term operation at medium voltage are 0.35 and 0.25, respectively [3]. Table 1 shows the recommended values of flicker planning and emission levels.

Table 1. Flicker planning and emission levels

Flicker severity factor	*Planning levels*		*Emission levels*
	MV	**HV**	**MV and HV**
Pst	0.9	0.8	0.35
Plt	0.7	0.6	0.25

One of the alternative solutions for decreasing flicker emissions of wind power integration is DSTATCOM control technique and a storage device in point of common coupling (PCC) [4]. Technical constraints with respect to wind power integration in distribution network may in general be related to short circuit capacity in parts of the grid and/or the unfavorable effect wind power integration can have on power quality.

In this paper, challenges arising from abovementioned situations are investigated, and viable approaches to enable acceptable operation of large wind farms in distribution systems are pointed out.

A simulation tool was developed using MATLAB in order to examine the impacts of wind power integration on the operation of distribution networks. Using this tool, the advantages of the examined approach, i.e. significantly decreased voltage fluctuations and the improved voltage quality were highlighted. A series of simulations were performed considering flicker emissions of switching operations. It was found that for an installed capacity of higher than 5.63 MVA the distribution network was led to unstable operation.

Furthermore, it was shown that by dividing the maximum apparent power by the rated power of each wind turbine, the total number of wind turbines is obtained. A load flow program should be used to verify the voltage variations. All the voltage variations should be equal to or less than 5 percent in comparison with the case that no wind turbine is integrated to the grid.

WIND POWER INTEGRATION APPROACH

In order to determine maximum capacity of a wind farm for interconnecting to the distribution network, maximum apparent power and flicker emission should be calculated. In [2] a unique approach is presented. The algorithm can be shown as the following steps:

1- Form impedance matrix using input data
2- Compute the three-phase short circuit power
3- Compute the maximum apparent power injected by the wind farm
4- Make the linear interpolation of turbine data
5- Compute flicker emission caused by continuous and switching operation
6- Determine true value of wind turbines

A simulation model for a type of wind turbines interconnected to the electric network has been developed. The bus impedance matrix is formed using step-by-step formation.

Using pre-fault voltages (E_0) and short circuit currents (I_f), short-circuit power (S_k) is calculated by:

$$S_k = E_0 I_f \tag{1}$$

According to IEC-61400-21, flicker emission during continuous operation and short-term and long-term flicker emission in switching operation shall be estimated applying (2-4) below [5,6,7]:

$$P_{st\Sigma} = \frac{18}{S_k}\left(\sum_{i=1}^{N} N_{10,i}.(k_f(\psi_k).S_n)^{3.2}\right)^{0.31} \quad (2)$$

$$P_{lt\Sigma} = \frac{8}{S_k}\left(\sum_{i=1}^{N} N_{120,i}.(k_f(\psi_k).S_n)^{3.2}\right)^{0.31} \quad (3)$$

$$P_{st\Sigma} = P_{lt\Sigma} = \frac{1}{S_k}\sqrt{\sum_{i=1}^{N}(c(\psi_k, v_a).S_n)^2} \quad (4)$$

where, P_{st} and P_{lt} are short-term and long term flicker emissions, S_n is rated apparent power of the wind turbine, S_k is short-circuit power at PCC, $c(\psi_k, v_a)$ is flicker coefficient related to grid impedance phase angle (ψ_k) and annual average wind speed (v_a), and N_{10} and N_{120} are number of switching operations of the individual wind turbine within a 10 min and 120 min period, respectively. Generally, P_{lt} is smaller than P_{st} to consider the fact that the irritability caused by the flicker is a cumulative effect and increase with the time [2]. Taking into account these fluctuations, a strategy of integrating wind power based on maximum apparent power that could be injected in each bus is proposed.

The steady state voltage change is defined as

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ . \\ . \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} \frac{|S_{\max 1}|}{|S_{k1}|}\cos(\psi_1 + \vartheta_1) \\ \frac{|S_{\max 2}|}{|S_{k2}|}\cos(\psi_2 + \vartheta_2) \\ . \\ . \\ . \\ \frac{|S_{\max n}|}{|S_{kn}|}\cos(\psi_n + \vartheta_n) \end{bmatrix} \quad (5)$$

where $S_{\max 1}$ is maximum apparent power of the wind farm and ϑ is phase angle of the impedance seen from PCC [2]. Equation 5 is only valid for $\cos(\psi_n + \vartheta_n) > 0.1$. It is interesting to note that the aforementioned simulation tool will be developed in future work.

MODELING CASE STUDY

This case study investigates the impact of Binalood wind farm on the distribution electricity network with respect to the voltage quality. Binalood wind farm is located 60 kilometers away from Mashhad the capital city of Khorasan Razavi in northeast of Iran and is furnished with 43 Sabaniroo S47-660 wind turbines with the total capacity of 28.4 MW. Annual average wind speed in this region is 9 m/s. Table 2 shows the rated parameters for this wind turbine. The generated power is streamed to the national power grid. This radial distribution network is consists of some medium voltage overhead 20 kV feeders, supplying various types of loads, mostly residential and commercial with the maximum demand of 22 MVA at a power factor of 0.96 lagging.

Table 2. Wind energy conversion system S47-660 parameters

Symbol	*Parameter*	*Value*	*Unit*
$P_{r\text{-}wt}$	Wind turbine rated power	660	kW
D_{wt}	Rotor diameter	47	M
V_{cutin}	Cut -in wind speed	4	m/s
V_{rated}	Rated wind speed	15	m/s
V_{cutout}	Cut-out wind speed	25	m/s
$V_{to\text{-}wt}$	Rated terminal voltage	690	V
F	Operational frequency	50	Hz
I_{rated}	Rated terminal current	628	A
PF	Power factor	0.88	--

In addition, the radial distribution network is fed by two 15 MVA distribution transformers. The transformer ratio is 63/20 kV and the short circuit power at this point is equal to S_k = 136.5 MVA.

In this paper, the radial distribution network is simplified and represented by 15 most significant nodes related to main buses or major loads. All of the other consumers are aggregated into these nodes. Figure 1 illustrates the simplified radial distribution network.

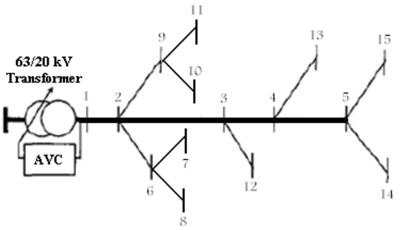


Fig. 1. Simplified distribution system

Since the data of the power quality measurement of Sabaniroo S47-660 wind turbines are not available so far, in this analysis, the data for power quality estimation of wind turbines according to IEC 61400-21 for DEWI WTN600 wind turbines as presented in table 3 were applied [6]. Using linear interpolation, the other values for flicker coefficient, flicker step factor and voltage change factor could be achieved. Bus loads and line data for the given case are presented in appendix. Impedance modeling of loads is employed for this purpose.

SIMULATION RESULTS

Binalood wind farm is now connected through 4 feeders in which one of them is fed by another sub-transmission substation and is not considered in this analysis. The three nodes that wind farm is considered to be integrated are nodes 8, 10 and 12. Grid impedance phase angle and short circuit power were simulated and are shown in table 4.

Table 3. Flicker parameters estimation

Network impedance phase angle, ψ_k	**30°**	**50°**	**70°**	**85°**
Annual average wind speed, V_a	Flicker coefficient, c(ψ_k, V_a)			
6 (m/s)	8	8	8	8
7.5 (m/s)	8	8	8	8
8.5 (m/s)	8	8	8	8
10.5 (m/s)	8	8	8	8
Case of switching operation:	Start-up at cut-in wind speed			
Maximum number of switching operations, N_{10}:	12			
Maximum number of switching operations, N_{120}:	120			
Flicker step factor, $K_f(\psi k)$:	0.2	0.2	0.2	0.2
Voltage change factor, $K_U(\psi k)$:	0.4	0.4	0.3	0.3
Case of switching operation:	Start-up at rated wind speed			
Maximum number of switching operations, N_{10}:	1			
Maximum number of switching operations, N_{120}:	12			
Flicker step factor, $K_f(\psi k)$:	0.4	0.4	0.4	0.4
Voltage change factor, $K_U(\psi k)$:	1.0	0.8	0.7	0.5

Moreover, maximum apparent power that can be injected to the nodes and true maximum apparent power with respect to the number of wind turbines, which is a multiple of wind turbine rated apparent power are illustrated in figure 2. As the figure reveals, $S_{tmax}$is approximately equal to S_{max}.

Table 4. Grid impedance phase angle, short-circuit current, pre-fault voltage and short circuit power at PCC.

Bus No.	*Angle ψ,°*	*I_f (p.u.)*	*E_0 (p.u.)*	*S_k (MVA)*
8	58.52	0.498	0.994	49.51
10	57.73	0.470	0.982	46.17
12	57.25	0.447	0.968	43.31

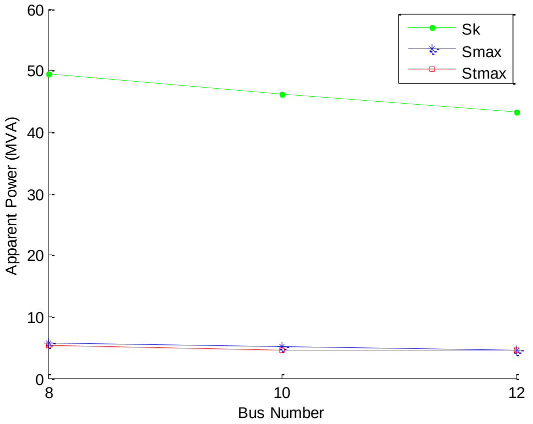


Fig. 2. Apparent powers at bus 8, 10 and 12.

Flicker emissions according to equations (2-3) were calculated for these nodes. Knowing the value of the flicker emissions and emission levels, the true number of wind turbines is given in figure 3. As it can be obviously seen, long term flicker emission values are smaller than short term flicker emission values. The graph shows that flicker emission limits the number of acceptable wind turbines to 7, 6 and 4 for buses 8, 10 and 12, respectively.

A load flow program was performed to verify voltage variation after wind power integration. Results shown in table 5 confirm that all the voltage variations are less than 5 percent.

Table 5. Load flow results.

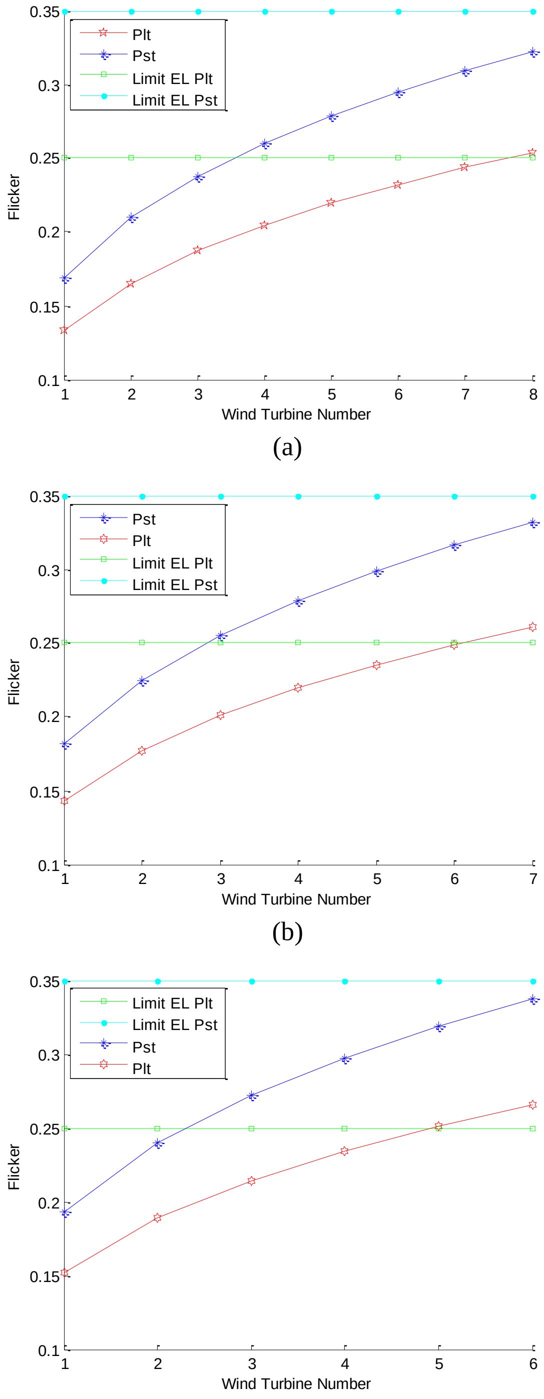
Bus No.	*E_0 (p.u.)*	*E_{wf} (p.u.)*	*ΔE (%)*
8	0.994	1.012	1.78
10	0.982	1.015	3.25
12	0.968	1.009	4.06

CONCLUSION

The purpose of this study was to determine the impacts of large amounts of wind power on distribution network. Binalood wind farm consists of 43 Sabaniroo S47-660 wind turbines with the total capacity of 28.4 MW as a case study was investigated in this paper. Every wind turbine is equipped with a step-up transformer that connects it to the grid. It was also shown that using the proposed approach, optimal wind power that can be integrated to the utility, without violating the power-quality regulations is obtained.

As expected, voltage variations exceed acceptable limits at some nodes, due to surplus wind power injection.

Therefore, it is recommended to develop new transmission lines or upgrade the existing lines to a level in which wind power can be injected safely with an acceptable level of voltage variations and power quality. A more thorough investigation of the wind power interconnection impacts on power system is also recommended.



(a)

(b)

(c)

Fig. 3. Flicker emission: a) bus 8; b) bus 10; c) bus 12

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APPENDIX

Table 6. Bus loads and line data.

From Bus i	*To Bus j*	*Length (km)*	*R (Ω/km)*	*X (Ω/km)*	*Load at Bus j (MW)*
1	2	0.1	0.2681	0.2789	9.775
2	3	6.5	0.2681	0.2789	1.565
2	6	9.8	0.2681	0.2789	0.25
2	9	10.7	0.2681	0.2789	1.835
3	4	7.2	0.2681	0.2789	0.6
3	12	9.1	0.2681	0.2789	0.315
4	5	0.2	0.2681	0.2789	0.575
4	13	2.2	0.2681	0.2789	1.55
5	14	4	0.2681	0.2789	1.225
5	15	2.7	0.2681	0.2789	0.325
6	7	0.5	0.4434	0.4528	0.5
6	8	3.4	0.2681	0.2789	--
9	10	2.3	0.4434	0.4528	--
9	11	0.4	0.4434	0.4528	0.475