Grid Compliance and Power Quality Comparison of Wind Plants with Different Turbine and Grid Types

F. B. Uzunlar*‡, Ö. Güler**, Ö. Kalenderli***

*Energy Institute, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey

**Energy Institute, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey

***Department of Electrical Engineering, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey

(barisuzunlar@gmail.com, onder.guler@itu.edu.tr, kalenderli@itu.edu.tr)

‡ F. B. Uzunlar, Energy Institute, Istanbul Technical University, 34469, Maslak, Istanbul, Turkey,

Tel: +90 532 372 3357, Fax: +90 212 285 3884, barisuzunlar@gmail.com

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Abstract- In this paper, different grid integration and generators used for wind plants is compared by means of quality of the power generated in plant and impact to the power system. Annual energy production and cost of a given wind plant are basis of the comparison. Technical and economical values of different type wind turbine generators are quantitatively evaluated by providing necessary electrical and cost calculations. In technical examination, grid compliance of a 30 MW wind plant with 13 units of asynchronous geared type turbine is investigated by using power system analysis software as per Turkish Grid Code. Steady state conditions of the wind power plant are evaluated by calculating the reactive power capability, load flow and short circuit analysis at first part of the paper. Secondly, low voltage ride through capability, system frequency and voltage test of the wind park are assessed. Similarly, same plant is considered to be equipped with 3.0 MW direct drive type turbines and technical study repeated with different grid type by means of electrical balance of plant. Finally, levelized cost of electricity calculation is done to observe economic effect of plant parameters in order to obtain maximum wind energy.

Keywords Energy Quality; Grid Connection Code; Direct Drive Turbine; Doubly Fed Induction Generator; Levelized Cost of Energy

1. Introduction

Most of the turbines operating in wind market have a classic design with three blades rotating with the wind, and this rotation moving of the blades is transmitted to the rotor of wind turbine via gearbox for electric production. As gearbox is removed from concept design at latest wind turbine technology, direct drive generators have become technically highly available and economically more feasible.

Several comparisons have been made between the direct drive and geared wind turbine generators (WTG) in literature. Tavner [1] and Echavarria [2] focused on how different converter design and the configuration concepts can affect all WTG reliability by directly comparing reliability of three WTG types: variable speeds with gearbox or direct drive (no gearbox: only synchronous generator), and fixed speed with gearbox.

Polinder et al. defined a typical WTG concept with a direct drive mechanism coupled to a synchronous generator (DDSG) and a three-stage gearbox (3GDFIG) in order to examine both wind turbine types from economical and design performance point of view where he highlights the requirement for future studies to better emphasize the availability and reliability advantages of different wind turbine designs [3].

Zhao et al. presented an algorithm where important technical specifications and key elements of a wind plant are included as inputs so that the electrical balance of the wind plant is optimized by means of both system reliability and generation cost [4].

Benini et al. explained another algorithm to optimize the geometrical data of the rotor design aiming to achieve the best economic performance between the cost and total energy efficiency of wind plant [5].

Kusiak et al. proposed an algorithm for interpreting WTG performance, where the aim is to minimize the judder of the tower and driver system while maximizing the wind power output [6].

Fuglsang and Thomsend studied an optimization method with a cost model for project specific design of WTGs and a load estimation method where levelized cost of electricity calculation (LCOE) is minimized [7].

Kusiak and Song presented an algorithm for WTG positioning according to wind profile with the objective of minimizing design constraint violations and maximizing the wind energy production [8]. Rasuo and Bengin studied on a wind park layout to determine the optimum locations of WTGs within the plant for maximum energy yield [9]. Mustakerov and Borissova presented an optimization algorithm to determine optimal siting, number and type of WTGs for given wind farm and wind conditions [10] where also Spertino et al. studied on a case to chose most suitable WTG locations for a site [11].

Technical and economical comparison of turbine types with and without gearboxes has also been made [12] by doing levelized cost of energy calculation as per cost reviews of wind energy in recent years [13, 14].

Both technical and economical optimization is aimed in this paper by doing calculations in order to effectively use wind resource at a location [15, 16]. So, two different studies have been conducted on technical and economic aspects.

In technical section, grid compliance of a 30 MW wind plant with 13 units of asynchronous geared type turbine is investigated by using power system analysis software as per Turkish Grid Code [17] both in dynamic and steady state conditions for interconnection to the grid and grid code compliance verification by making conclusions. At that time, same plant is considered to be equipped with 3.0 MW direct drive type turbines and technical study repeated steady and dynamically on a real electrical network by creating different scenarios like changing inter array cable characteristics, transformer short circuit impedances, generator type and rated generator power, rotor diameter, tower height, etc. for investments that can be made to settle problems during the grid compliance of wind plant at interconnection point.

In the last section, cost of energy calculation is done to observe economical impact of plant parameters in order to obtain maximum wind potential.

2. Wind Plant Properties

A 30 MW wind plant with 13 units of asynchronous geared type turbine and same plant with a turbine replacement of 3.0 MW direct drive type are investigated by using power system analysis software as per Turkish Grid Code. Table 1 is shown coupling bus characteristics.

Each turbine is connected to collection system via a 31.5/0.69 kV transformer. The transformers are equipped with tap changers (NLTC). The properties of this transformer are given in Table 2.

Table 1. Maximum and minimum values of bus impedance and short circuit power at point of common coupling (PCC)

WPP 170 kV	Bus Impedance				Short Circuit Power 10^6 [VA]	
	Reactance (per unit)		Resistance (per unit)			
	(1)*	(2)**	(1)	(2)	(1)	(2)
	0.07222	0.07416	0.01265	0.01572	1329	1352
Base values: Sb = 100 MVA, Vb = 154 kV *(1) Maximum value **(2) Minimum value						

Table 2. WTG transformer data

Parameters	3.0 MW Direct Drive Generator	2.3 MW Geared Generator
Rated Apparent Power [MVA]	3.6	3.0
Short Circuit (SC) Impedance [%]	6	6
Rated Input Voltage [kV]	31.5	31.5
Rated Output Voltage [kV]	0.69	0.69
Transformer Connection Form (Vector Group)	Dyn11	Dyn11
Tap Changer [%]	± 2 × 2.5	± 2 × 2.5
Losses without Load [kW]	3.2	3
Losses with Load at 75ºC [kW]	32	30

Wind park is coupled to the network via one 154/34.5 kV power transformer. Secondary voltage is controlled with an on load tap changer (OLTC) and it also has a voltage regulator (AVR). The data of main transformer is given in Table 3.

Table 3. Main power transformer data

Parameters	3.0 MW Direct Drive Generator	2.3 MW Geared Generator
Rated Power [MVA]	62.5	62.5
Short Circuit (SC) Impedance [%]	11.84	13.5
Rated Input Voltage [kV]	154	154
Rated Output Voltage [kV]	31.5	31.5
Transformer Connection Form (Vector Group)	YNyn0	YNyn0
Stage of Tap Changer [%]	± 12 × 1.25	± 12 × 1.25
Losses without Load [kW]	32	36
Losses with Load at 75ºC [kW]	250	285

The size of the cable belongs to its placement within the farm. WTGs are connected to collection system in the main transformer substation through cabling network with given parameters in Table 4.

Table 4. Cabling system parameters of 2.3 and 3 MW WTGs

Cable Parameters	Copper Cable (N2XSY) Values for 3 MW Direct Drive WTG	Aluminium Cable (NA2XSY) Values for 2.3 MW Geared WTG
Conductor Cross Section [mm^2]	70 – 500	185 – 400
Reactance [mΩ/km]	147 - 109	193 - 171
Resistance [mΩ/km]	271 - 45	182 - 100
Shunt Capacitance [nF/km]	205 – 295	205 – 271
Rated Nominal Current [A]	274 – 765	399 – 577

3. Simulations

Simulation model of Wind Power Plant (WPP) with similar topology in Fig. 1 is studied by using power system analysis software based on one line diagram of existing farm under operation. WTGs are considered as PV-nodes when limit of the reactive power is not obtained and produce an active power and as PQ-nodes when the reactive power is at boundary value during steady state where load flow, short circuit and reactive capability of WPP are examined. The network data given in Table 1 is exported to software where dynamic models of WTG and wind farm level controls are also embedded.

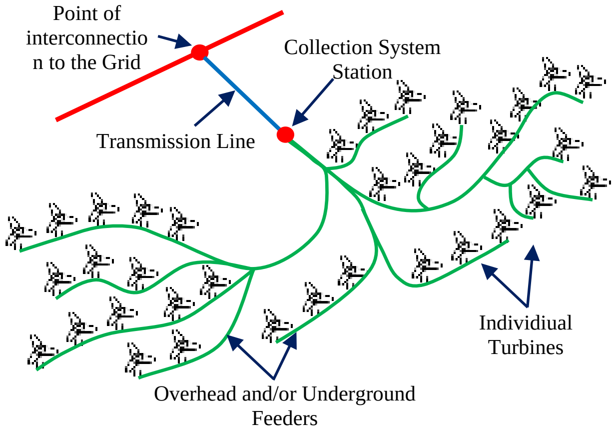


Fig. 1. Wind power plant simulation model.

Low Voltage Ride Through (LVRT) capability, system frequency and voltage test of the wind park are assessed. Similarly, same plant is considered to be equipped with 3.0 MW direct drive type turbines and technical study repeated with different grid type by means of electrical balance of plant. Finally, LCOE calculation is done to observe economical impact of plant parameters in order to obtain maximum wind energy.

3.1. *Steady State Analysis*

3.1.1. *Reactive Power Capability*

As first step of steady-state analysis, reactive power capability of one turbine is studied. Wind plant should continue its operation at all points within the boundaries given in grid code where reactive power and active power are measured at point of interconnection. PCC is defined as the primary side of the main transformer of wind power plant.

Reactive powers of both 2.3 MW geared and 3.0 MW direct drive WTGs are given in Fig. 2 and Fig. 3 from manufacturer's turbine data documentation.

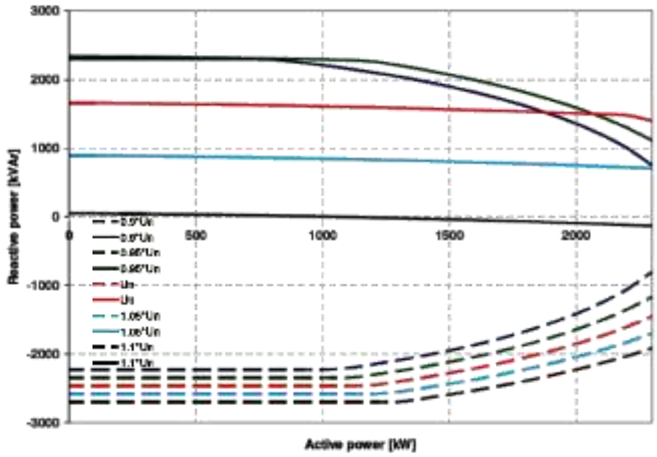


Fig. 2. Reactive power capability of 2.3 MW geared WTG.

Wind turbine generators are considered as PV-nodes when the reactive power limit is not obtained and as PQ-nodes when the reactive power is at boundary during steady state analysis. The turbines should continue their operation in a range of 0.9 lagging to 0.9 leading power factors at the secondary side of WTG's transformer both at balanced voltage and nominal frequencies according to "Grid Performance Document" of turbine manufacturer.

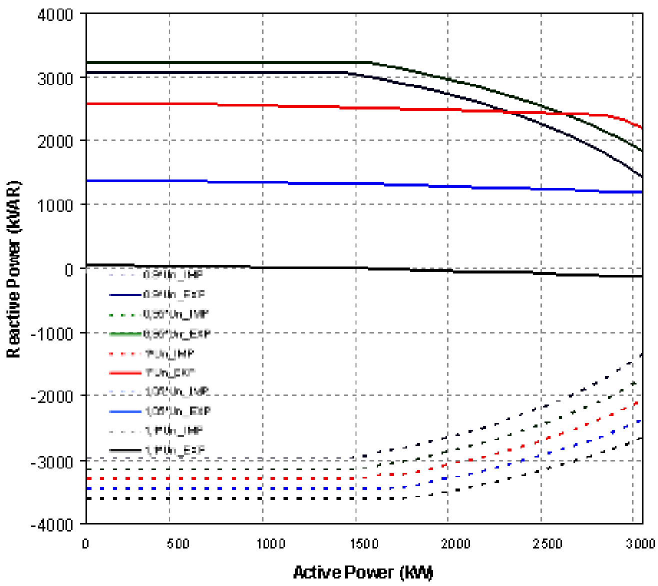


Fig. 3. Reactive power capability of 3 MW direct drive WTG

Analysis identifies the reactive power capability of wind plant at point of interconnection considering the individual capability of each turbine. Simulation results of reactive power and comparison with grid code for 2.3 MW geared WTG with 7 MVAr capacitor solution is given as in Fig. 4:

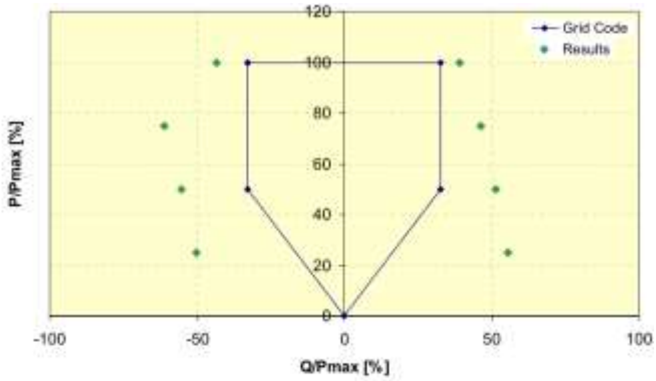


Fig. 4. Reactive power simulation results of 2.3 MW geared WTG (with 7 MVAr capacitor bank).

Simulation results of reactive power and comparison with grid code for 3.0 MW Direct Drive WTG is given as in Fig. 5:

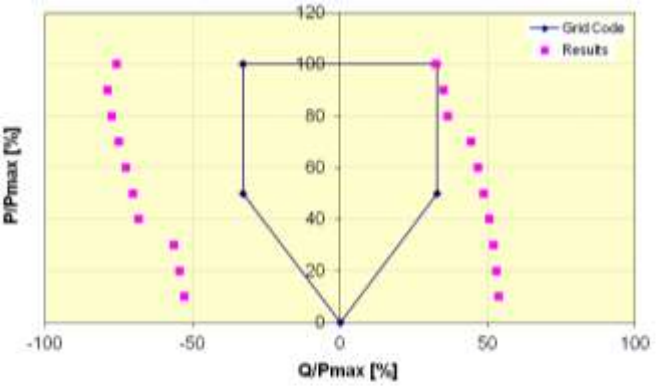


Fig. 5. Reactive power simulation results of 3.0 MW direct drive WTG.

It is seen according to results given in Fig. 4 and Fig. 5 that in case if tap changer position of transformer is "-1", results are within the limits of normal operation case as required in grid code. Using tap changer is recommended since it is a more reliable and robust structure than capacitor.

3.1.2 Load Flow Study

This analysis study is also simulated as per reactive power graphics. Analysis results are given for under and over excited cases during maximum active power production according to defined operating condition. Typical equivalent representation of single wind generator is given in Fig. 6 for simulation reference.

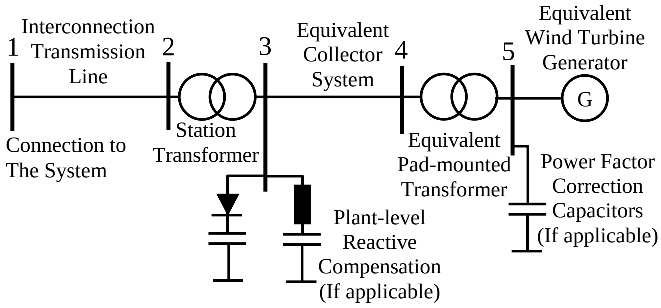


Fig. 6. Equivalent power flow for single wind generator.

Load flow result for normal operation condition (P = 2.3 and 3 MW at v = 100 %) are given in Table 5. Results of load flow analysis for 2.3 MW geared WTG shows that minimum busbar voltage ratio at main medium voltage bus is V/V_n = 99.42 %.

Table 5. Simulation results of load flow at normal operation for 2.3 and 3 MW WTGs.

WTG Type	2.3 MW geared	3 MW direct drive
Bus Name	V/V_n [%]	V/V_n [%]
High Voltage (HV) Level (154 kV)		
MAIN HV	100.00	100
Medium Voltage (MV) Level (31.5 kV)		
MAIN MV	99.42	99.65
WTG MV1	99.67	99.90
WTG MV2	99.68	99.91
WTG MV3	99.60	99.83
WTG MV4	99.58	99.81
WTG MV5	99.64	99.87
WTG MV6	99.67	99.90
WTG MV7	99.70	99.93
WTG MV8	99.76	99.99
WTG MV9	99.74	99.97
WTG MV10	99.70	99.93
WTG MV11	99.65	99.88
WTG MV12	99.59	99.82
WTG MV13	99.50	99.73
Low Voltage (LV) Level (0.69 kV)		
WTG LV1	103.17	103.70
WTG LV2	103.18	103.76
WTG LV3	103.10	103.82
WTG LV4	103.08	103.84
WTG LV5	103.14	103.73
WTG LV6	103.17	103.82
WTG LV7	103.20	103.97
WTG LV8	103.26	104.15
WTG LV9	103.24	104.29
WTG LV10	103.20	104.42
WTG LV11	103.15	104.51
WTG LV12	103.09	104.65
WTG LV13	103.00	104.68

Maximum loaded low voltage cable belongs to WTG8 with a percentage of 92.18 %. Maximum loaded generator transformer belongs to WTG8 with a percentage of 76.92 %. Maximum loaded medium voltage cable has a percentage of

56.96 %. Main power transformer has a load percentage of 47.74 %.

Results of load flow analysis for 3.0 MW direct drive WTG shows that there is no violation in limits of bus voltages and voltage results are in 95-105 % range. Cable loads are below 100 % and overload is not observed.

Maximum overload for copper cable is 98.76 % and 98.71 % for aluminium. Maximum load in turbine transformers are 97.7 % in maximum reactive power consumption. Since this operation value is above grid compliance, it is assumed not to be observed but in point of common coupling, it can be observed if wind park is requested to operate in voltage control.

3.1.3 *Short Circuit Calculation*

In order to size switching equipment and check if short circuit current surpasses maximum permissible current, three phase short circuit analysis is calculated according to defined operating conditions of the plant. The short circuit impact of the plant to the point of interconnection is evaluated as output of this simulation.

One-phase to ground maximum-minimum, two-phase maximum-minimum and three phase minimum short circuit analyses are also performed to check response of the system according to each short circuit type for the same operating conditions and analysis results are given in Table 6.

Table 6. Simulation results of three-phase peak short circuit currents for 2.3 and 3 MW WTGs

WTG Type	2.3 MW geared		3 MW direct drive	
Bus Name	I_k" [kA]	S_k" [MVA]	I_k" [kA]	S_k" [MVA]
High Voltage (HV) Level (154 kV)				
MAIN HV	5.32	1419.85	5.82	1553.3
Medium Voltage (MV) Level (31.5 kV)				
MAIN MV	8.96	489.04	9.06	494.4
WTG MV1	6.67	364.03	7.31	398.8
WTG MV2	6.48	353.42	7.11	387.7
WTG MV3	6.98	380.56	6.83	372.5
WTG MV4	7.29	397.73	6.55	357.4
WTG MV5	6.83	372.57	7.79	425.1
WTG MV6	6.52	355.89	7.60	414.4
WTG MV7	6.14	335.16	7.33	399.8
WTG MV8	6.53	356.52	7.19	392.2
WTG MV9	6.94	378.57	6.91	377.2
WTG MV10	7.31	398.96	6.65	362.6
WTG MV11	7.63	416.51	6.40	349.2
WTG MV12	7.95	434.01	6.17	336.5
WTG MV13	8.46	461.54	5.82	317.3
Low Voltage (LV) Level (0.69 kV)				
WTG LV1	42.54	50.83	51.79	61.9
WTG LV2	42.39	50.67	51.61	61.7
WTG LV3	42.74	51.08	51.36	61.4
WTG LV4	42.95	51.33	51.10	61.1
WTG LV5	42.64	50.96	52.19	62.4
WTG LV6	42.41	50.69	52.02	62.2
WTG LV7	42.11	50.33	51.77	61.9
WTG LV8	42.43	50.70	51.64	61.7
WTG LV9	42.72	51.05	51.36	61.4
WTG LV10	42.96	51.34	51.08	61.0
WTG LV11	43.16	51.58	50.82	60.7
WTG LV12	43.34	51.80	50.57	60.4
WTG LV13	43.60	52.11	50.16	60.0

Results of SC analysis for 2.3 MW geared WTG shows that LV busbar with maximum SC current belongs to WTG LV13 with a value of 43.60 kA. MV busbar with maximum SC current belongs to MAIN MV with a value of 8.96 kA. Maximum SC current in HV level is 5.32 kA. LV cable with minimum SC withstand is WTG LV13 with a value of 1.61 sec. MV cable with minimum SC withstand is WTG MV1 with value of 4.18 sec.

Results of SC analysis for 3.0 MW direct drive WTG shows that SC effect of 5.58 kA and 0.25 kA has been added to HV main bus, from grid and wind plant respectively. SC current of 154 kV main bus is 5.82 kA. SC effect of 154/31.5 kV main transformer is 7.70 kA to 34.5 kV main bus with 31.5 kA for maximum SC withstand. Total SC effect of cables coming from plant to this bus is 1.36 kA. Three-phase maximum SC current of 34.5 kV main bus is 9.06 kA and bus withstand is achieved, SC current limit is not violated in this case. Three-phase maximum SC effect of each wind turbine generator for LV bus is 5.15 kA.

3.2. *Dynamic Analysis*

To initiate dynamic study by analysing voltage and frequency tests with low voltage ride through (LVRT) capability, same model that is developed for the steady-state analysis is used. For these studies, simulation program is used according to based on turbine manufacturer's dynamic model.

3.2.1. *Test for LVRT*

If the voltage at point of wind farm interconnection is above the lower contour of area given in Fig. 7, then wind plant should stay connected. Active power will drop during fault and below slope rates are required after the fault:

▪ If fault voltage is above coloured area then 200 P_{rated}/ms until the existing active power and

▪ If fault voltage remains within coloured range then 50 P_{rated}/ms until the existing active power.

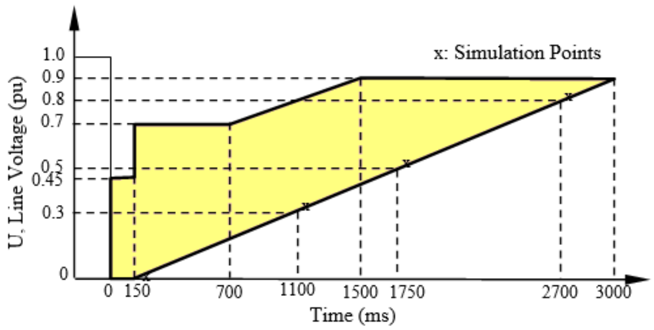
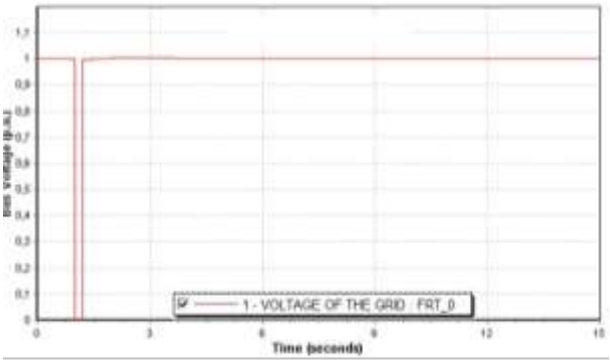


Fig. 7. LVRT capability required by grid code.

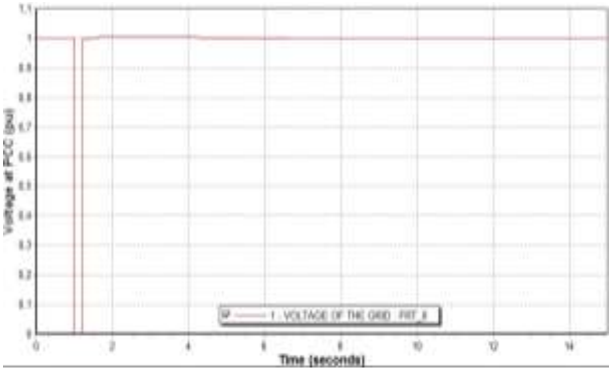
Grid code indicates two different slopes for power. One of them is 5 %/s and other is 20 %/s. It has been warned by grid operator that it is also compliant if the wind turbine is in capacity to give 20 %/s or higher for these two locations.

The required reactive current injection is 10 % dead-band for voltage fluctuations and out of this band; wind turbines should provide reactive current equals to 2 % of I_{rated} for each percent voltage drop. In order to present response of wind plant to voltage dips, a series of simulations has been realized.

Simulation results for LVRT test are shown in Fig. 8 and Fig. 9 for both types of WTGs.

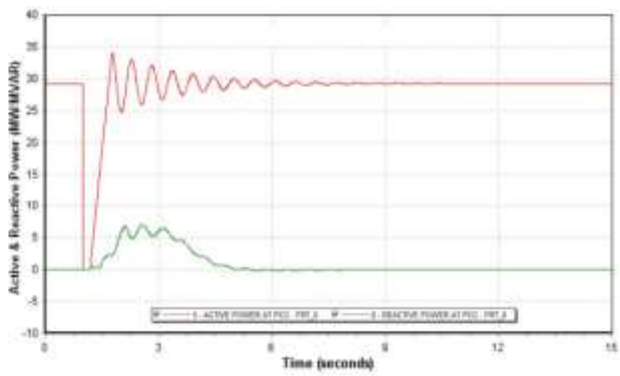


a)



b)

Fig. 8. LVRT simulation results of bus voltage at PCC for a) 2.3 MW geared WTG; b) 3.0 MW direct drive WTG at 0 % residual voltage and 200 ms fault duration.



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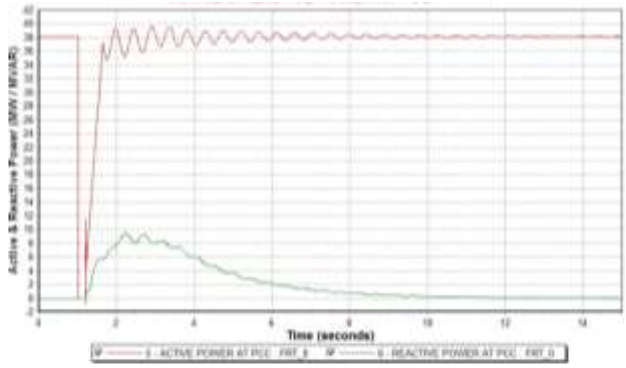


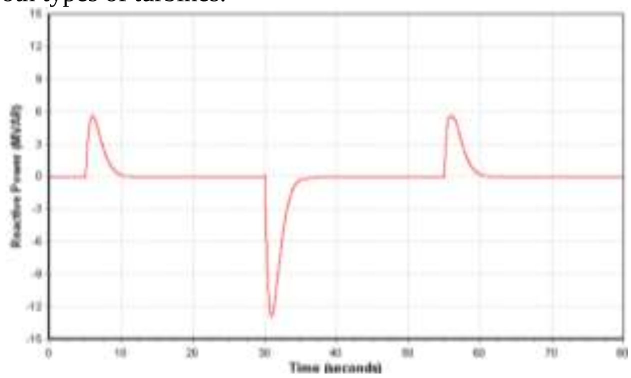
b)

Fig. 9. LVRT simulation outputs for active and reactive powers for a) 2.3 MW geared WTG; b) 3.0 MW direct drive WTG at 0 % residual voltage and 0.2 s fault duration.

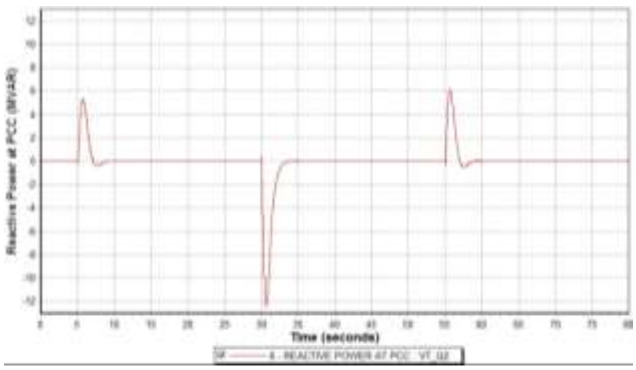
As per simulation results, WTGs enter LVRT mode and work stably with fault for 0 %, 30 %, 50 %, and 80 % residual voltages and bus voltage has achieved its nominal value again right after 0.2 s fault duration which is within the limits.

3.2.2 Test for Voltage Control

To observe wind farm reactions to voltage fluctuations, a voltage test is performed both when the wind plant is operating in constant power factor mode as 1.00 and in voltage control mode with 4 % droop setting. Simulations during 80 s both for power factor and voltage control are realized. Studies are also performed by grid voltage changed step by step. Fig. 10 and Fig. 11 show voltage test results for both types of turbines.

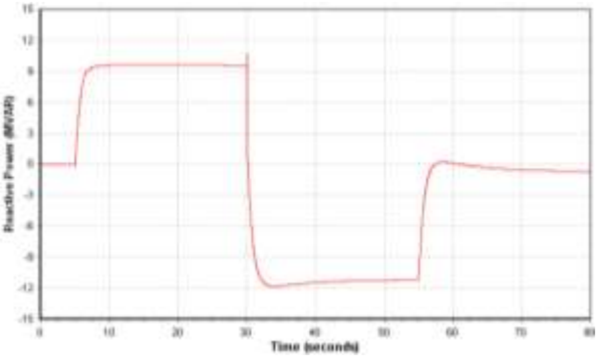


a)

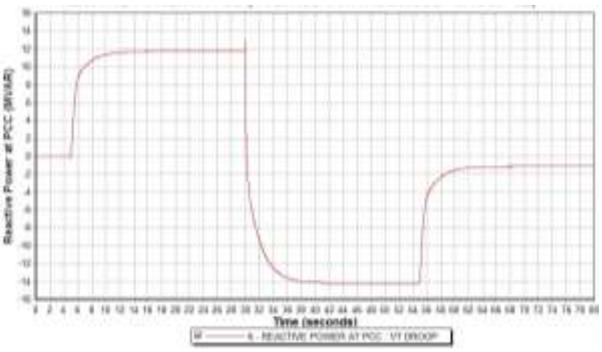


b)

Fig. 10. Reactive power variation in voltage test simulation (constant power factor) for a) 2.3 MW geared WTG; b) 3.0 MW direct drive WTG.



a)



b)

Fig. 11. Reactive power variation in voltage test simulation (voltage control-droop 4%) for a) 2.3 MW geared WTG b) 3.0 MW direct drive WTG

It is seen from figures that steady state reactive power is not changed in constant power factor mode (cosφ = 1) and it changes according to droop setting in voltage control mode.

3.2.3 Frequency Response Test

No additional unit is allowed get in operation when network frequency is over 50.2 Hz. Wind turbine frequency response should stay within limits of given grid code.

Fig. 12 shows permitted frequency response graphic of wind turbine as per grid code [15] where one can conclude that it is aligned with the grid code compliance by means of frequency response. The turbines can also operate in frequency range between 47 Hz and 52 Hz. Numerical results for both turbine types are shown in Table 7.

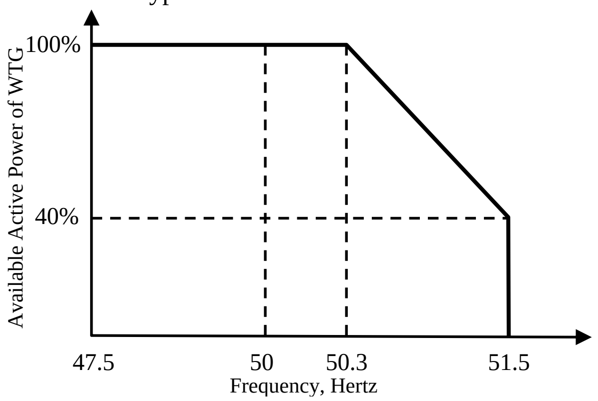


Fig. 12. Permitted frequency response graphic of wind turbine as per grid code.

4. Economic Analysis

LCOE is the cost of electricity production which includes central production, total construction and financing costs; returns on capital and depreciation during plant's economic lifetime.

Costs can be either adjusted to eliminate the inflation impact or levelled in current monetary values. LCOE is a method to compare renewable energy technologies adopted for electricity production.

Table 7. Frequency test result for 2.3 and 3 MW WTGs.

Frequency [Hz]	WTG type			
	2.3 MW geared		3.0 MW direct drive	
	Stabilized power [MW]	Power reduction per 100 mHz [%]	Stabilized power [MW]	Power reduction per 100 mHz [%]
50.0	29.213	0	38.190	0
50.3	29.213	0	38.190	0
50.9	20.243	5	26.464	3.6 ~ 4
51.5	11.272	5	14.736	3.6 ~ 4

LCOE is most known and used model in energy projects which can be defined and calculated as below:

$$LCOE = \frac{(CapEx \times FCR) + OpEx}{(AEP_{net} / 1000)} \quad (1)$$

where CapEx stands for total capital expenditures (CapEx) and fixed charge rate (FCR) is calculated as below:

$$FCR = \frac{d(1+d)^n}{(1+d)^n - 1} \times \frac{1-(T \times PVdep)}{1-T} \quad (2)$$

with discount rate (d), operational lifetime (n), tax rate (T) and present value of depreciation (PVdep).

Operational expenditures (OpEx) is sum of annual levelized land lease (LLC), operational (OPER) and maintenance costs (MAIN) given as:

$$OpEx = LLC + OPER + MAIN \quad (3)$$

and net average annual energy production (AEPnet) is calculated with net capacity factor (CFnet) as below :

$$AEPnet = MWnet \times 8760 \times CFnet \quad (4)$$

Both technical and economic information are given in Table 8 for each turbine type.

Table 8. Technical and economic information given for LCOE calculation of both 2.3 and 3.0 MW WTGs

WTG Configuration	2.3 MW 101 m RD, 80 m HH	3.0 MW 113 m RD, 85 m HH
Main Parameters of WTG		
Rated Power [MW]	2.3	3
Rotor Diameter [m]	101	113

Hub Height [m]	80	85
Drivetrain Design Type	Geared	Direct Drive
Gross AEP [MWh/MW/year]	3919	3944
Gross Capacity Factor [%]	44.7	45.0
Availability [%]	97	98
Losses		
Copper Losses [MWh/year]	63	189
Iron Losses [MWh/year]	53	87
Converter Losses [MWh/year]	92	370
Gearbox Losses [MWh/year]	404	0
Array MV Cable (Al/Cu) Losses [kW]	364	267
Turbine Step-Up Transformer [MWh/year]	192	264
Main Power Transformer [MWh/year]	74	120
Total Losses and Unavailability [%]	29	27
AEPnet [MWh/MW/year]	2765	2820
Net Capacity Factor [%]	31.6	32.6
Turbine Capital Cost		
Rotor [k€]	499	499
Tower [k€]	529	529
Generator Active Material [k€]	40	40
Generator Construction [k€]	40	40
Gearbox [k€]	295	295
Converter [k€]	54	54
Total Generator System Cost [k€]	429	429
Other Wind Turbine Parts Appr. [k€]	554	554
Total Cost [k€]	2010	2010
Total Cost [k€/MW]	874	874
Balance of System		
Development Cost [k€/MW]	21	21
Engineering Management [k€/MW]	14	14
Foundation [k€/MW]	42	42
Site Access and Staging [k€/MW]	34	34
Assembly and Installation [k€/MW]	31	31
Electrical Infra. [k€/MW]	107	107
Financial Costs		
Market Price Adjustment [k€/MW]	-7	-7
Construciton Financing Cost [k€/MW]	36	36
Contingency Fund [k€/MW]	74	74
Total Capital Expenditures		
CapEx [k€/MW]	1224	1220
Total Operational Expenditures		
Operations [€/kW/year]	15	13
Land Lease Cost [€/kW/year]	8	8
Maintenance [€/kW/year]	28	26
OpEx [€/kW/year]	51	47
Fixed Charge Rate		
Discount Rate [% d]	6.6	6.6
Economical Operational Life [N year]	20	20
Tax Rate [% T]	38.9	38.9
Depreciation [%PVDep]	79.8	79.8
Fixed Charge Rate [%]	10.3	10.3

As per LCOE calculation results of both type WTGs given in Table 9, one can conclude that per megawatt cost of energy for direct drive turbine is lower than geared one.

Table 9. LCOE Calculation for both 2.3 MW Geared and 3.0 MW Direct Drive WTGs

WTG Configuration	2.3 MW 101 m RD, 80 m HH	3.0 MW 113 m RD, 85 m HH
Levelized Cost of Energy		
CapEx [k€/MW]	1224	1220
Fixed Charge Rate [%]	10.3	10.3
OpEx [€/kW/year]	51	47
AEPnet [MWh/MW/year]	2765	2820
Levelized Cost of Energy [€/MWh]	64	60

5. Conclusion

Most of the wind turbines operating in wind market has conventional design which are gearbox driven machines but after recent technological developments, direct drive WTGs have become technically highly available and economically more reasonable since no gearbox exists in direct drive construction.

Double fed induction generator (DFIG) having three-stage gearbox is widely chosen commercial solution as it is lightest and cheapest model with standard components but having lower energy production due to the high losses in the gearbox since it mostly consists standard materials as copper and iron where one cannot expect major improvements in cost deduction or performance.

Since direct-drive permanent-magnet generator (DDPM) has benefits of a fully rated converter and does not have brushes and a gearbox, it is usually best solution depending on site profile. Besides, energy production of it is a bit higher than other generator systems with gearbox since active material weight of the generator for the same air-gap diameter is less which makes it much more attractive although it is more expensive. One can expect further developments of this generator due to drop in prices of power electronic converters, permanent magnets and also optimization is still possible.

LCOE calculation results of both type WTGs show that per megawatt cost of energy for direct drive turbine is lower than geared one. Even with the same grid considerations at point of common coupling, installed base power of a single wind plant can be increased up to 30 % with just changing turbine type and configuration. Further improvements can be achieved in power quality [18, 21] by electrical balance of plant with changing internal grid parameters like type of array cable used within plant and short circuit impedance of main power transformer so that energy losses in long-term calculations during lifetime of plant can be reduced as well.

References

[1] Tavner, P. J., Bussel, G. J. W. V., and Spinato, F., "Machine and converter reliabilities in wind turbines", in Proc. 3rd Power Electron. Mach. Drives Conf. (PEMD 2006), Cork, Ireland, pp. 127–130, March 2006.

[2] Echavarria, E., Hahn, B., van Bussel, G. J. W., and Tomiyama, T., "Reliability of wind turbine technology through time", Trans. ASME (J. Sol. Eng.), vol. 130, no. 3, pp. 0310051–0310058, Aug. 2008.

[3] Polinder, H., Van Der Pijl, F. F. A., de Vilder, G., and Tavner, P. J., "Comparison of direct-drive and geared generator concepts for wind turbines", IEEE Transactions on Energy Conversion, vol. 21, no. 3, pp. 725–733, Sep. 2006.

[4] Zhao, M., Chen, Z., Blaabjerg, F., "Optimization of electrical system for offshore wind farms via genetic algorithm", IEEE Transactions on Renewable Power Generation, vol. 3, no. 2, pp. 205–216, 2009.

[5] Benini, E., Toffolo, A., "Optimal design of horizontal-axis wind turbines using blade-element theory and evolutionary computation", Journal of Solar Energy Engineering, vol. 124, no. 4, pp. 357–363, 2002.

[6] Kusiak, A., Zhang, Z., Li, M., "Optimization of wind turbine performance with data driven models", IEEE Transactions on Sustainable Energy, vol. 1, no. 2, pp. 62–76, 2010.

[7] Fuglsang, P., Thomsen, K., "Site-specific design optimization of 1.5–2.0 MW wind turbines", Journal of Solar Energy Engineering, vol. 123, no. 4, pp. 296–303, 2001.

[8] Kusiak, A., Song, Z., "Design of wind farm layout for maximum wind energy capture", Renewable Energy, vol. 35, no. 3, pp. 685–694, 2010.

[9] Raˇsuo, B. P., Bengin, A. C., "Optimization of wind farm layout", FME Transactions, vol. 38, pp. 107–114, 2010.

[10] Mustakerov, I., Borissova, D., "Wind turbines type and number choice using combinatorial optimization", Renewable Energy, vol. 35, no. 9, pp. 1887–1894, 2010.

[11] Spertino, F., Cocina, V., Di Leo, P., Pastorelli, M., "Choice of the most suitable wind turbine in the installation site: A case study", 4*th International Conference on Renewable Energy Research and Applications*, Palermo, pp. 1631-1634, 22-25 November 2015.

[12] McMillan, D., Ault, G. W., "Techno-economic comparison of operational aspects for direct drive and gearbox-driven wind turbines", IEEE Transactions on Energy Conversion, vol. 25, no. 1, pp. 191-198, Sep. 2009.

[13] Mone, C., Stehly, T., Maples, B., Settle, E., "2014 Cost of wind energy review", National Renewable Energy Laboratory, Technical Report NREL/TP-6A20-64281 October 2015.

[14] Hamane, B., Doumbia, M. L., Bouhamida, B., Draou, A., Chaoui, H., Benghanem, B., "Comparative study of PI, RST, sliding mode and fuzzy supervisory controllers for DFIG based wind energy conversion system", International Journal of Renewable Energy Research, vol. 5, no. 4, pp. 1174–1185, 2015.

[15] Tazi, N., Chatelet, E., Meziane, R., Bouzidi, Y., "Reliability optimization of wind farms considering constraints and regulations", 5*th International Conference on Renewable Energy Research and Applications*, Birmingham, pp. 389-394, 20-23 November 2016.

[16] Kıymaz, Ö., Yavuz, T., "Wind power electrical systems integration and technical and economic analysis of hybrid wind power plants", 5*th International Conference on Renewable Energy Research and Applications*, Birmingham, pp. 158-163, 20-23 November 2016.

[17] Turkish Grid Code for Wind Connection, Annex 18, 2013.

[18] Kharchouf, I., Essadki, A., Nasser, T., "Wind system based on a doubly fed induction generator: Contribution to the study of electrical energy quality and continuity of service in the voltage dips event", International Journal of Renewable Energy Research, vol. 7, no. 4, pp. 1892–1900, 2017.

[19] Amalorpavaraj, R. A. J., Palanisamy, K., Umashankar, S., Thirumoorthy, A. D., "Power quality improvement of grid connected wind farms through voltage restoration using dynamic voltage restorer", International Journal of Renewable Energy Research, vol. 6, no. 1, pp. 53–60, 2016.

[20] Enrique, E., Moser, S., Bailey, T., "Capacitor banks contribution to arc-flash – Application to solar and wind farm substations", *6th International Conference on Renewable Energy Research and Applications*, San Diego, pp. 389-394, 5-8 November 2017.

[21] Panah, S. F., Ghannad, G. A., Panah, T. F., "Reactive power compensation in wind power plant with short circuit in power plant line via UPFC", *5th International Conference on Renewable Energy Research and Applications*, Birmingham, pp. 173-176, 20-23 November 2016.