Grid Connection and Power Quality Optimization of Wind Power Plants

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Abstract

This paper covers the integration of the wind turbines with the national grids which includes the quality of the power generated at the wind plants, the impact to the power systems and the details of connection systems. The system has been considered in detail together with PSS-E (Power System Simulation for Engineering) software program. The scope of the study consists of two parts: technical and economical. 30 MW Wind Power Plant consisting of 13 pieces of 2.3 MW asynchronous WTG of type 690 V, 50 Hz is investigated due to the grid compliance of WPP according to Turkish Grid Code for Wind Turbines (Annex 18) in technical part. Firstly, the reactive capability of the wind power plant and comparison of it with the requirements of the Grid Code is determined. Secondly, the low voltage right through (LVRT) capability of the wind park is assessed. Finally, the system frequency and voltage test shall be applied. In the economic section, by changing some of technical parameters, cost-benefit analysis of the economic impact will be made in order to get use of maximum wind potential that could be obtained.

1. Introduction

Wind turbine technology improves and demand on renewable energy world widely increases, transmission network also requires expanding and developing in parallel. Existing grid will not meet the growing demand in the near future [1, 2].

In this study, the topic is aimed to be considered from both technical and economical view for optimization by doing analysis and consequently using maximum wind potential in the region.

The analysis is planned to consist of two distinct phases. First, the wind power plant is analysed in steady state conditions in order to connect to the national grid and aimed to verify compliance with the grid code criteria by making inferences. Then, during the grid connection of wind farms at point of common coupling (PCC) is dynamically examined on a real transmission network, the cost of investments that can be made for settlement of connection problems is carried out with different scenarios.

The main purpose of the work to be carried out is the realization of cost-benefit analysis to be used for a maximum wind potential in that area with the optimization of the investment that can be made both in transmission systems and wind plant. By examining the available information on the criteria of connection to the grid system of wind energy production, constitution a resource for future studies and creation a reference for investments to be made to the transmission system is aimed.

2. Methods

During the technical and economical studies to be done on energy transmission and quality investments necessary for wind energy production, calculation of technical losses with load flow analysis; observation of the most influential parameters on the voltage profile in the changes of network with transient state analysis; investigation of system behavior that may occur during and after the connection with dynamic analysis; power quality and harmonics, protection and coordination with network model analysis are planned. The cost of investments regarding to the transmission network development and improvement projects is planned during economic studies.

2.1. Steady State Analysis of Transmission Grid

2.1.1 Reactive Power Capability

For steady-state analysis, reactive power capability of a single wind turbine generator is examined. The Turkish grid code defines reactive power capability requirements which are shown in figure 1. The wind park should be able to operate at all points inside the polygon shown in the figure, where the active power and reactive power are measured at the PCC. The PCC will be the RES_TM HV kV bus (high voltage side of the main transformer) for WPP.

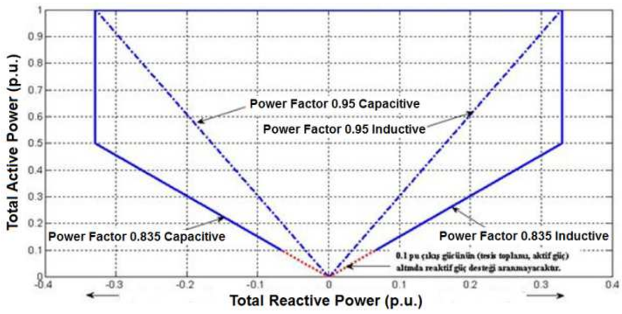

Fig. 1. Reactive power capability requirements according to the Turkish grid code

2.1.2 Load Flow Analysis

Load flow analysis is simulated according to reactive power curves. According to defined operating condition, load flow results are given during maximum active power production for over-excited and under-excited situations, respectively. Load flow results for different active-reactive power are given for defined operating condition.

2.1.3 Short Circuit Analysis

Three phase maximum short circuit analysis provides to evaluate if short circuit current of buses exceed or not maximum allowed current and sizing of switching equipments. For this purpose 3-phase maximum short circuit is simulated for defined operating condition of the plant. An important output of this simulation is the short circuit contribution of wind power plant to the grid connection point.

Three phase minimum, 2-phase maximum-minimum and 1-phase to ground maximum-minimum short circuits are also analyzed for the same operating condition to evaluate behaviour of the system according to each short circuit.

2.2. Dynamic Analysis of Transmission Grid

The model that has been developed for the steady-state study has been used as a starting point for the dynamic study to assess the LVRT capability, voltage and frequency tests. The simulation program is applied for these investigations, as turbine manufacturer releases a dynamic simulation model for this platform.

2.2.1 Low Voltage Ride Through (LVRT) Test

The LVRT requirements set forth in the Turkish grid code are graphically shown in figure 2. If the voltage at the PCC of the wind power plant remains above the lower border of area 2, the plant is required to remain connected. During the fault, active power will be reduced. After the fault, the following ramp rates are required:

- 0.2 Prated/s up to the available active power if the fault is in area 1, and
- 0.05 Prated/s up to the available active power if the fault is in area 2.

These indicates two different power slopes of 5%/s and 20%/s but TEIAS informed that, there will be no problem if the wind turbine is capable of giving 20%/s or more for both regions.

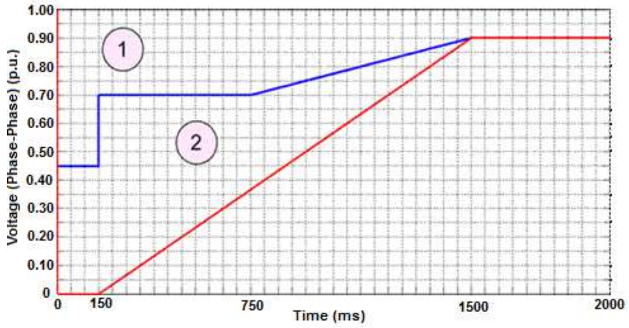

Fig. 2. Low-voltage ride through capability required by the Turkish Grid Code.

The required reactive current injection in Turkish Grid Code is shown in Figure 3. It requires a 10% dead-band for voltage fluctuations and it indicates that out of this range, WTGs shall supply reactive current equals to 2% of I_{rated} for each percent voltage drop.

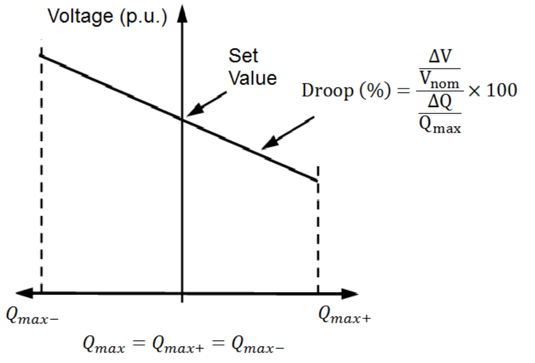

Fig. 3. Required reactive current injection during voltage fluctuations.

2.2.2 Voltage Control Test

A voltage test is applied to simulate how the WPP reacts to voltage fluctuations, both when the WPP is operated in voltage control mode with 4% droop setting, and operated in constant power factor mode (constant power factor as 1.00). Step changes for actual voltage of the network are applied and simulations of 80 s for power factor and voltage control have been performed.

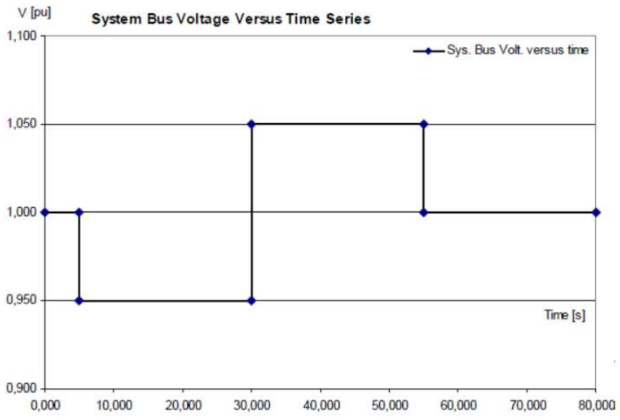

Fig. 4. Bus voltage setpoint variation in time.

2.2.3 Frequency Response Test

For the conditions that grid frequency is over 50.2 Hz no additional WTG shall get in operation. WTG frequency response shall remain in the bold line given in the Figure 5.

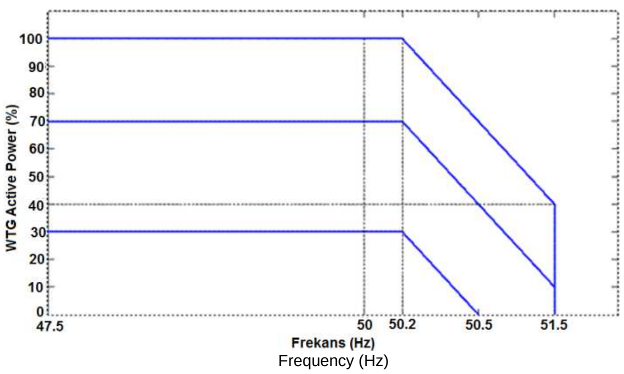

Fig. 5. Required frequency response curve of WTG.

3. Simulation Results

A simulation model of the WPP is implemented in PSS®E software based on the single-line diagram. For the purpose of dynamic simulations the network data has then been exported to PSS®E, where the data are amended with the dynamic models of WT and park level controls.

Table 1. 154 kV TSO SS INFEDEER Bus Characteristics

WPP 154 kV SS	Positive Sequence Impedance				Short Circuit Power (MVA)	
	R (p.u.)		X (p.u.)			
	Max.	Min.	Max.	Min.	Max.	Min.
	0.01572	0.01265	0.07222	0.07416	1352	1329
Vbase = 154 kV, Sbase = 100 MVA						

For steady state purposes, WTGs are modelled as produce an active power output between 0 and 2.3 MW and as PV-nodes as long as the reactive power limit is not reached and as PQ-nodes when the reactive power is at the limit.

Table 2. Wind Turbine Generator Characteristics

Name	Sn (MVA)	Vr (kV)	R/X (p.u.)	Xd"sat (%)
WTG	2.3	0.69	0.15	35.5

Each WTG is connected to the inter-array cable network through a 31.5/0.69 kV transformer. The relevant data of this transformer are shown in table 3. The transformers are provided with no load tap changers (NLTC).

Table 3. Wind Turbine Transformer Characteristics

Rated Power	3.0 MVA
Short Circuit Impedance (u_k)	6 %
Rated Primary Voltage	31.5 kV
Rated Secondary Voltage	0.69 kV
Vector Group	Dyn 11
Tap Changer	NLTC $\pm 2 \times 2.5\%$
No Load Losses (Po)	3.2 kW
Total Load Losses (Pk)	31 kW at 75 C

The wind park is connected to the grid by means of one 154/34.5 kV transformer. The data of this device is listed in table 4. The transformer is equipped with an automatic voltage regulator (AVR) controlling the voltage at the secondary side with an on-load tap changer (OLTC).

Table 4. Wind Plant Main Power Transformer Characteristics

Rated Power	62.5 MVA
Short Circuit Impedance (u_k)	11.84 %
Rated Primary Voltage	154 kV
Rated Secondary Voltage	31.5 kV
Vector Group	YNyn0
Tap Changer	OLTC $\pm 12 \times 1.25\%$
No Load Losses (Po)	32 kW
Total Load Losses (Pk)	250 kW at 75 C

The WTGs are connected to the medium-voltage bus bars in the WPP substation through the inter array cable network. For the modeling of these cables, an NA2XSY cable type was assumed, parameters of which are displayed in table 5. The diameter of the cable depends on its location in the WPP.

Table 5. Inter Array Cable Characteristics

Aluminum	Parameter	Value
185 mm^2	Conductor Cross Section	185 mm^2
	Resistance	0.182 Ω / km
	Reactance	0.193 Ω / km
	Shunt Capacitance	205 nF / km
	Rated Nominal Current	399 A
240 mm^2	Conductor Cross Section	240 mm^2
	Resistance	0.143 Ω / km
	Reactance	0.186 Ω / km
	Shunt Capacitance	227 nF / km
	Rated Nominal Current	458 A
300 mm^2	Conductor Cross Section	300 mm2
	Resistance	0.110 Ω / km
	Reactance	0.180 Ω / km
	Shunt Capacitance	244 nF / km
	Rated Nominal Current	510 A
400 mm^2	Conductor Cross Section	400 mm^2
	Resistance	0.100 Ω / km
	Reactance	0.171 Ω / km
	Shunt Capacitance	271 nF / km
	Rated Nominal Current	570 A

3.1 Steady State Analysis Results

The reactive power capability of a single WTG is given at user information document of turbine manufacturer. For the steady-state calculations, WTGs are modelled as PV-nodes as long as the reactive power limit is not reached, and as PQ-nodes when the reactive power is at the limit.

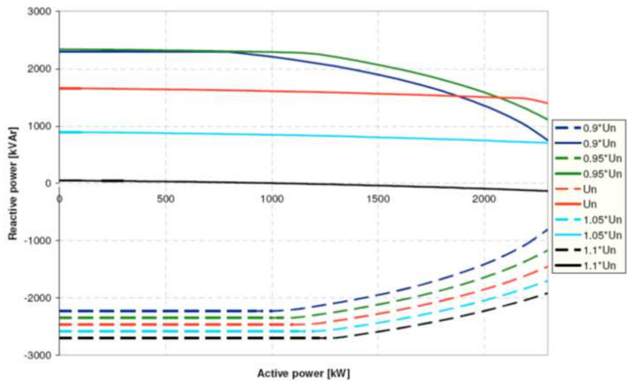

Fig. 6. Reactive Power Capability of Wind Turbine Generator

According to "Grid Performance Document" of turbine manufacturer, the turbines are able to operate in a power factor range of 0.9 leading to 0.9 lagging at the low voltage side of the wind turbine transformer at nominal balanced voltage and nominal frequency. The study should identify the reactive power capability of the WPP at the PCC taking into consideration the individual capability of the WTGs.

Table 6. MVAr Limits for Active Power Generation Percentage in Normal Operating Conditions with 7 MVAr Capacitor Solution

MVAr Value for %100 MW	MVAr Value for %75 MW	MVAr Value for %50 MW	MVAr Value for %25 MW
12.905	14.718	16.073	17.042
-12.032	-18.419	-17.174	-16.109

Table 7. Numerical Simulation Results with 7 MVAr Capacitor Solution

		Grid Code	Sim. Results
	P / Pmax [%]	Q / Pmax [%]	Q / Pmax [%]
Under excited	100	-32.9	-41.2
	75	-32.9	-63.1
	50	-32.9	-58.8
	25	-16.9	-55.2
Over excited	100	32.9	44.2
	75	32.9	50.4
	50	32.9	55.1
	25	16.9	58.4

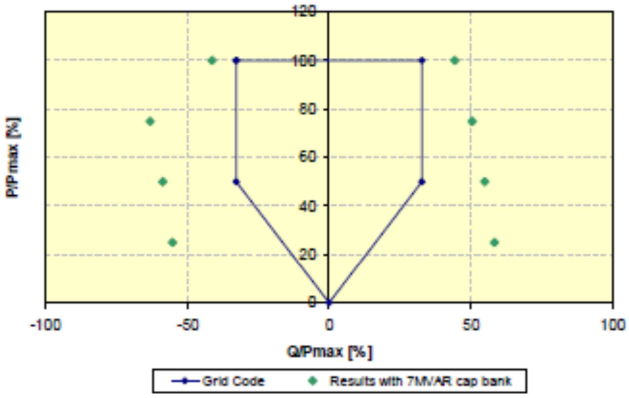

Fig. 7. Graphical Representation of Simulation Results and Comparison with Grid Code (with 7 MVAr Capacitor Solution)

According to the above results, it is seen that values are within the limits for normal operating position as claimed in network regulations in cases when the position of transformer tap changer "-1". However, since it creates a more robust structure and more reliable solution than capacitor, it is advised to use tap-changer option.

3.2 Dynamic Analysis Results

A series of simulations has been performed to show the behavior of the WPP to voltage dips that are at just below the prescribed curve. Schematic representation of FRT simulation points are shown in Figure 8.

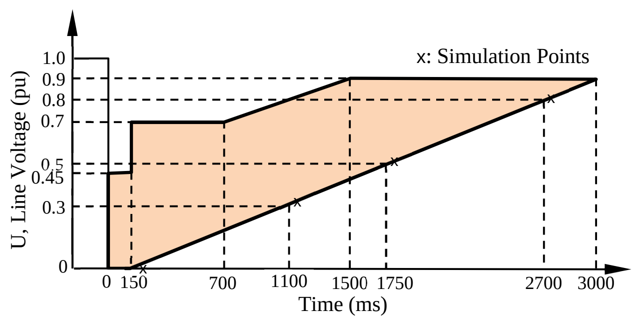

Fig. 8. Schematic representation of FRT simulation points

The simulation results show that the wind turbines enter low voltage ride through mode (LVRT-mode) and ride stably through the fault for the 0%, 30%, 50%, and 80% residual voltage cases. The converter system reacts as it senses the voltage drop because of the fault. This case is shown in Figure 9 for voltage level of 50%. This voltage level is being the closest one to the maximum reactive power support. Maximum reactive power was reached within 40 ms.

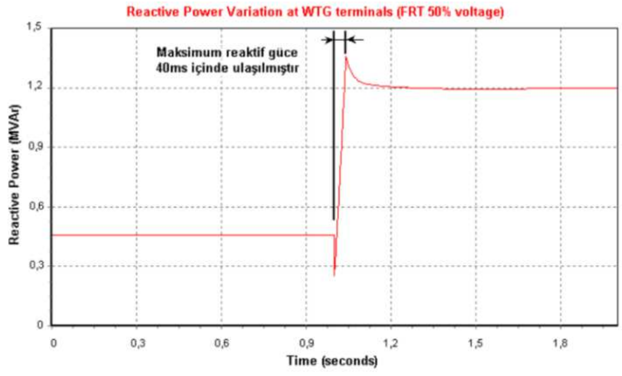

Fig. 9. Reactive power response of WTGs when %50 voltage drop fault occurs in PCC

Table 8. Reactive power value of WTGs when %50 voltage drop fault occurs in PCC

Time (seconds)	Reactive Power (MVAr)
1.000	0.4596
1.005	0.3776
1.010	0.5047
1.015	0.6379
1.020	0.7760
1.025	0.9182
1.030	1.0640
1.035	1.2132
1.040	1.3610

Although the grid code requires a ramp rate that is dependent on the actual fault profile, it is informed that a 20%/s or higher ramp rate is acceptable for both regions. Fluctuations in voltage support with reactive current grid code is given as a comparative figure 10. As seen from the graph wind turbine can generate more reactive than those required by the generator current.

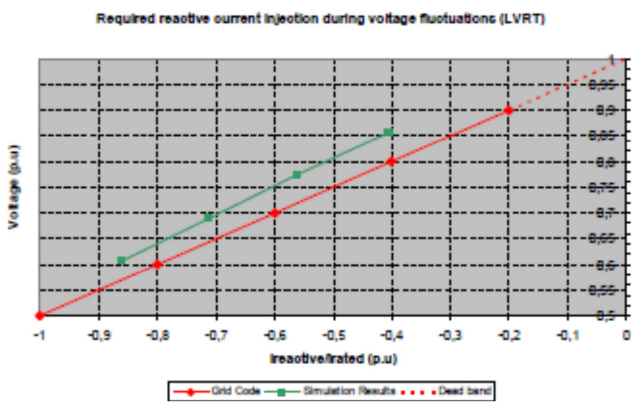

Fig. 10. Required reactive current injection during voltage fluctuations (LVRT) and comparison with grid code

According to the graphics and the table 9, it can be concluded that this configuration is compliant with the grid code requirements in frequency. Turbines are able to operate in the frequency range of 47 Hz to 52 Hz.

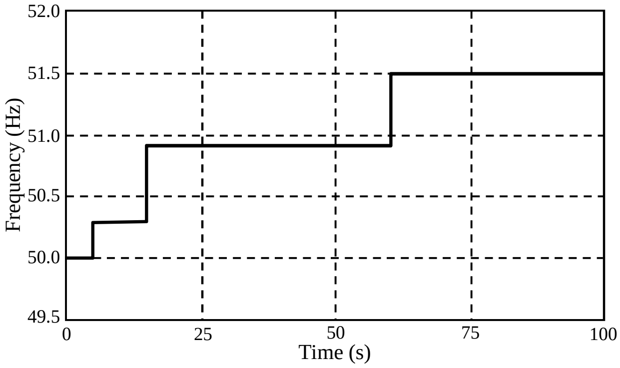

Fig. 11. Frequency variation during frequency test

Table 9. Reactive power value of WTGs when %50 voltage drop fault occurs in PCC

Frequency (Hz)	Stabilized Power (MW)	Power reduction per 100 mHz (%)
50	29.213	0
50.3	29.213	0
50.9	20.243	5
51.5	11.272	5

4. Conclusions

Parallel with developments in technology, installed capacity of grid connected wind turbines has increased. Increasing penetration level of wind farms has effects on grid [3-7]. Before wind farms are installed, integration with grid is analyzed and suitability with grid code is investigated. In this study, a Wind Power Plant which under operation was researched in PSSE software. At first, steady state analysis was done and bus voltages were examined in the situation of operation. Flow rates of transmission lines should be controlled because load flow directions of related buses can be changed.

According to grid code [8-11], in case of a fault wind farms should stay connected to grid in certain circumstances. In the analyses, full-scale frequency converter wind turbines stayed connected to the grid in required situations. In the dynamic analyses, reactive power support was investigated. Low voltage ride through, voltage control and frequency response tests are applied as well.

When simulation results are compared with previous studies [9, 10], it can be concluded that they are aligned with each other. Analysis including economic methodologies is planned to be addition to technical static and dynamic studies. The results of this analysis aim to achieve optimization of the investments that can be made [12-15]. Maximum of actual wind potential is aimed to be used with this optimization. Capacity increase of WPPs with transmission line extensions and / or upgrades is examined. Network development plans for future grid can be done.

As the next step of this study, suitable investment scenarios like changing turbine type or power, replacing cable section or type, upgrading power transformer technical characteristics, etc. to increase plant capacity may be investigated. By using the wind potential in the region at the highest level, with the optimum investment in the wind power generation plants and in the transmission system for achieving more efficient production, particularly with the passage of the wind instead of the energy resources depending on outside the country, social welfare to country economies is planned to be contributed.

5. References

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