

Wind Farm Modeling for Steady State and Dynamic Analysis

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Abstract—This paper focuses on PSS/E modeling of wind farms of Doubly-fed Induction Generator (DFIG) type and their impact on issues of power system operation. Since Wind Turbine Generators (WTG) don't have the same characteristics as synchronous generators, the appropriate modeling of wind farms is essential for transmission system operators to analyze the best options of transmission grid reinforcements as well as to evaluate the wind power impact on reliability and security of supply. With the high expected penetration of wind power into the power system a simultaneous loss of Wind Farm generation will put at risk power system security and reliability. Therefore, the main wind grid code requirements concern the fault ride through capability and frequency operation range of wind turbines. In case of grid faults wind turbines have to supply a definite reactive power depending on the instantaneous voltage and to return quickly to normal operation.

Keywords—Power System transients, PSS/E dynamic simulation Double-fed Induction Generator.

I. INTRODUCTION

THE proper modeling of wind farm projects in systems studies is becoming increasingly important to system operators. In the past decade, wind power has evolved into a significant renewable energy source which continues to grow rapidly. Wind farms are growing in size and complexity and they consist of many units with significant power output. The increased size of wind power projects and the development of large wind parks bring about a number of opportunities and challenges [1]. The location of wind farm installation is based on good wind conditions and favorable economic and environmental condition of selected site. However these good wind conditions often coincide with relatively remote parts of power systems. In a power system there are always limitations as to how much power can be transmitted from one point to another point. The limitations depend on thermal limits, angle stability limits or voltage stability limits. Because of the limited extension of the Kosovo power system this process is particularly challenging. In view of the increasing interest in connecting wind farms to the Kosovo transmission grid, KOSTT (Kosovo Transmission System and Market Operator)

has undertaken an initiative to modify or extend own Grid Code to accommodate the particular capabilities and requirements of wind turbine generators (WTGs). The main issue here is the obligation the Wind Code places on the Generator/developer to provide a computer model of the WTG suitable for power system studies [2]. Some TSOs prefer to develop such a model themselves directly from a detailed mathematical description of the WTG. This however places the burden of responsibility onto the TSO to get the model right – which is impractical given the present state of modeling knowledge as well as because of having manpower-intensive requirements. Therefore KOSTT follows the practice of many other TSOs and places the obligation on the developer. In practice, we cannot expect wind farm developers to have the knowledge or skills to produce such a model – it will probably be provided by the wind turbine manufacturer (which in turn opens up confidentiality issues). In cases where the wind farm developer can not provide WTG model, KOSTT will use generic user model provided by the PSS/E (PTI).

The objective of this paper is to present the most significant characteristic and specific aspects of detailed wind farm modelling containing variable speed wind turbine units. A specific case study is analysed in order to identify the main requirements for wind farm connection to the Kosovo transmission grid. This paper will not address the detailed mathematics of PSS/E WTG user models which have been covered in many publications.

II. WIND FARM MODELING APPROACH

A. Overview

The modeling approach of wind farms is based on Wind Grid Code Requirements. The aim of Wind Grid Code is to provide a self-contained description of the technical and operational requirements that are to be met by the developers and operators of Wind-Powered Generating Stations (WPGS) that wish to connect to the Kosovo electricity grid and participate in the Kosovo electricity market. The Wind Code applies to all WPGSs that are or have applied to be connected to the transmission grid, with installed capacity of more than 10 MW. Developers of WPGSs intending to apply for connection to the transmission grid should be aware that they are required to provide Project Planning data at this level of detail at the time of filing the application in order for the TSO to carry out the relevant connection design and impact studies.

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Upon receiving the Connection Application, planning engineers will perform the impact and design study which cover:

- Impact of the Wind Farm connection on the power system security and reliability of supply.
- Design of the appropriate direct assets from the commercial boundary (110kV grid).
- Design of the necessary Infrastructure Reinforcement of the Transmission System.

All relevant planning data will be used for detailed modeling of Wind Farms using PSS/E simulation platform. In this case two common calculations are essential for assessing the impact of Wind Farms on security and reliability of power systems:

- Power flow calculation
- Transient stability

A power flow calculation is to determine the power flows on transmission lines and transformers and the voltage profile of system bus bars. This calculation is fundamentally important for the planning and design of the connection of wind farms to the transmission grid. N-1 Security criterion is essential for the proper design of transmission networks to ensure the security and reliability of power supply. System performance is compared to operating limits and criteria. Short Circuit calculations also play a very significant role for the proper selection of high voltage equipment and the setting of protection relays.

The objective of transient stability studies is to examine whether wind farms will have a negative effect on the transient stability of power system. The power system response for a defined set of disturbances, typically three phase and single phase faults cleared by tripping of transmission elements such as lines, transformers, generators or bus bars. The response of conventional or wind turbine generators is checked to see that all machines have an adequate stability margin, damping of power system oscillations is acceptable and that the voltage recovery following fault clearing is adequate.

B. Study case - Model description

The study was carried out on a large scale PSS/E model of the Southeast Europe regional network, comprising 9 interconnected areas representing respective individual national networks. The Kosovo power system is modeled in detail: only the 400kV and 220kV portion of the regional network is modeled. The model consists of three simulation data files: power flow data, dynamic data and sequence data. With the aim of analyzing the compliance of wind farms connection to the Kosovo transmission network with the Grid Code (Wind), the study considered the 80MW wind farm project application for the so called "Shtime" area which is known to have a very high potential of wind energy. The wind farm is planned to have 40 wind turbines, each rated at 2MW [3].

C. Design of wind farm connection to the transmission grid

The connection design of wind farms to the transmission grid is based on the requirements of the Grid Planning Code and Wind Code [4]. A deterministic approach based on power flow studies was taken. The selected connection configuration for the study case was based on two main planning criteria:

- The N-1 Security criterion (system should be able to withstand the loss of any single components like lines, transformers, cables or generators); and
- Economic criterion.

Figure 1 shows the configuration of wind farm connection to the 110kV transmission network for the study case. The Wind Farm Collector 35kV bus is connected via two 63MVA transformers to the 110kV transmission bus bar.

The power generated by the wind farm will be transmitted through two 110kV lines each thermally rated at 114MVA. The 110kV transmission point of connection of the wind farm is characterized as a relatively weak node compared to other 110kV nodes in the network which are located closer to generation sources. The maximum fault current at the 110kV connection point is $I_{k3}=13\text{kA}$, calculated in accordance with IEC 60909.

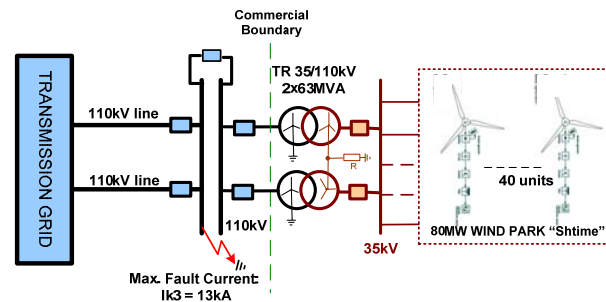


Fig. 1 Connection of 80MW Wind Farm "Shtime" in Transmission Grid

D. Modeling for steady state analysis

The power system modeling including wind turbines for steady state analysis in PSS/E version 32 is fairly simple, as shown in figure 2. Each individual wind turbine generator (WTG) is connected to a 690V bus and the WTGs are connected to the wind farm internal network through their 0.69/35 kV step-up transformers. The internal network is organized in eight rows or sections with five WTGs in each section. Within these rows, the wind turbines are connected through 35kV underground cables of different lengths and capacities depending on the location of each unit and the distance to the 35kV collector bus. The load flow solution provides the initial conditions for subsequent dynamic simulations. The maximum and minimum limits of active and reactive power must be respected in order to achieve a successful initialization. Inconsistencies between the power flow and the dynamic model will result in an unacceptable initialization.

Power flow modeling data for study case are shown in tables I, II, III, and IV.

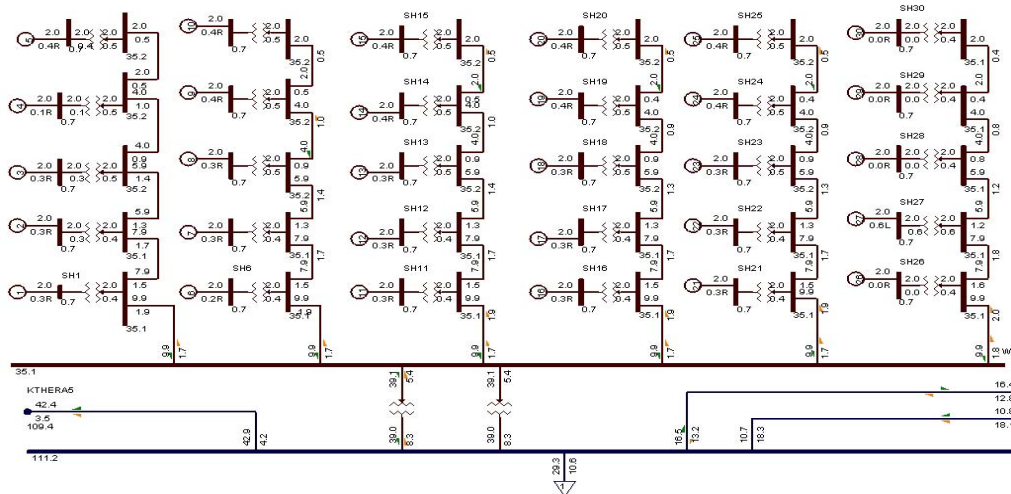


Fig. 2 Aggregated model of 80MW Wind Farm connected in transmission network

TABLE I
WIND TURBINE GENERATOR DATA

Symbol	Value	Unit
Sn	2	MVA
Qmax (Qmin)	0.65 (-0.65)	MVar
Pmax (Pmin)	2 (0.1)	MW
Zsource	0+j0.8	pu
Mbase	2.1	MVA

TABLE II
WIND TURBINE TRANSFORMER DATA

Symbol	Value	Unit
Sn	2.1	MVA
Unp/Uns	0.69/35	kV/kV
Ztr	0.0073+j0.06	p.u
Mbase	2.1	MVA

TABLE III
35/110kV - TRANSFORMER DATA

Symbol	Value	Unit
Sn	63	MVA
Unp/Uns	35/110	kV/kV
Ztr	0.0074+j0.196	pu
Ytr	0.0005 - j0.00149	p.u
Mbase	100	MVA

TABLE IV
35KV CABLE DATA

C.Sec.	I	R	X	C
mm2	Amp.	Ω/km	Ω/km	$\mu\text{F}/\text{km}$
50	175	0.391	0.23	0.16
150	350	0.126	0.2	0.24
240	465	0.076	0.19	0.28

E. Modeling for dynamic analysis

Initial dynamic model data file for the regional Power System is used for the study case. The dynamic data file so called dyr.file in PSS/E consist of dynamic parameter data for all conventional synchronous generators, turbines, exciters governors and other devices. The first step in dynamic

simulation using initial dynamic file is to enter the detailed dynamic model data for Wind Farm, which is saved in a file. This file contains a group of records, each of which defines the location of a dynamic WTG model in the grid along with the constant parameters of the model. The PSS/E version 31 and 32 provides a dynamic model for a DFIG wind turbine. The model includes generator, electrical control, wind turbine, and pitch control. Dynamic simulation is performed based on the load flow data that provide the transmission grid, load, and generator data [5]. In this study, a number of simulations are performed to investigate the WTGs model response subjected to grid disturbances. The most relevant disturbance for the study case is a three-phase symmetrical short-circuit fault on the 110kV interconnection bus as shown in figure 2. Additional fault events are simulated on the different busses of the Kosovo Transmission System to evaluate WTG dynamic pattern of behavior for various fault impedances.

F. PSS/E Dynamic model of DFIG

The variable speed wind turbine using DFIG are more popular technology which is used world-wide due to advantages such as high energy efficiency and controllability. DFIG is basically a standard, wound rotor induction generator with a voltage source converter connected to the slip-rings of the rotor. The stator winding are coupled directly to the grid and the rotor winding is connected to power converter as shown in figure 3.

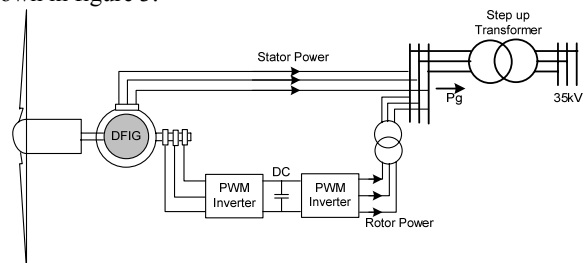


Fig.3 Double-Fed Induction Generator

The PSS/E wind turbine model WT3 was used for the dynamic simulation study with the objective of simulating the dynamic performance of a wind turbine employing DFIG technology. The generic WT3 model is included as a standard model in the Dynamic Model Library of PSS/E versions 31 and 32. The WT3 model can only be used when the generator is specified as a wind generator and not as conventional generator in the power flow data file [6].

The WT3 generic wind turbine model consists of the following main modules: WT3G generator/converter module, WT3E electrical control module, WT3T turbine module and WT3P pitch control module.

Figure 4 shows the interaction between these modules. Tables V, VI, VII and VIII, show the dynamic data for 2MW Double Fed Inductive Generator based on WT3 Generic Wind Model.

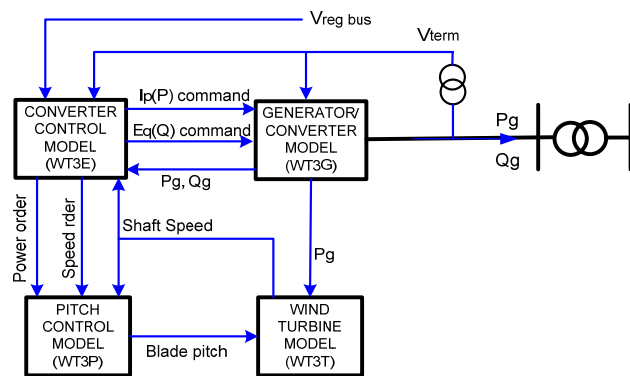


Fig.4 PSS/E DFIG generic model

TABLE V
GENERATOR MODEL WT3G1

Symbol	Value	Unit
Xeq	0.8	p.u
PII gain	30	con
PII integrator gain	0	con
PII maximum	0.1	cons
Turbine MW rating	2	MW
Nr. of lumped WT-s	1	integer

TABLE VI
TURBINE MODEL WT3T1

Symbol	Value	Unit
Vw	1.25	p.u
H	4.95	MW*sec/MVA
DAMP	0	p.u P/pu
Kaero	0.007	const.
Theta2	21.98	deg.
Htfac	0.875	Hturb/H
Freq1	1.8	Hz
DSHAFT	1.5	p.u P/pu

TABLE VII
ELECTRIC PART MODEL WT3E1

Symbol	Value	Unit	Symbol	Value	Unit
Tfv	0.15	sec	KQi	0.05	con
Kpv	18	p.u	VMINCL	0.9	con
Kiv	5	p.u	VMAXCL	1.2	con
Xc	0	p.u	Kqv	40	con
Tfp	0.05	sec	XIQmin	-0.5	con
Kpp	3	p.u	XIQmax	0.4	con
Kip	0.6	p.u	Tv	0.05	sec
PMX	1.12	p.u	Fn	1	con
PMN	0.1	p.u	Wpmin	0.69	p.u
QMX	0.309	p.u	Wp20	0.78	p.u
QMN	-0.309	p.u	Wp40	0.98	p.u
IPMAX	1.1	p.u	Wp60	1.12	p.u
TRV	0.05	sec	Pwp	0.74	p.u
RPMX	0.45	p.u	Wp100	1.2	p.u
RPMN	-0.45	p.u			
T_Power	5	sec			

TABLE VIII
PITCH MODEL WT3P1

Symbol	Value	Unit
Tp	0.3	sec
Kpp	150	pu
Kip	25	pu
Kpc	3	pu
Kic	30	pu
TetaMin	0	deg
TetaMax	27	deg
RTetaMax	10	deg/sec
PMX	1	p.u on Mbase

III. SIMULATION RESULTS AND DISCUSSIONS

A. Power flow simulation results

The power flow simulation on PSS/E 32 uses the full Newton – Raphson solution method. The load flow is calculated taking into consideration the deterministic approach. Regional winter peak demand and usual power exchange programs between TSOs of the South-East Europe power systems were considered for the base case scenario. The power flow simulations showed that some of the WTGs absorb different amounts of reactive power depending on the WTG terminal voltage level and on the different length and capacitance of the 35kV connection cables. In total, the wind farm internal network absorbs 10.4MVar of reactive power, with total active power losses of 0.8MW at maximum wind farm output.

No transformer or line in the transmission network was overloaded. The voltage profile complies with Grid Code requirements. An N-1 contingency assessment calculation was done to check the system security, resulting in the fact that no transformer or line in the transmission network was overloaded for any contingency. Thus, under steady state conditions, the wind farm has no negative impact on the security and reliability of the transmission system. On the contrary, the injection of active power into the 110kV network, so far removed from other generation sources, has a

beneficial impact by virtue of unloading some of the 110kV network and reducing power losses.

Additional simulation was done for light load condition of the regional power systems in order to check possible over-voltages in the Kosovo power system, resulting in the fact that the system voltages remained in acceptable range.

The main concern of operating with a high level of penetration of wind generation in the Kosovo power system relates to the impact of wind power variability on the power system balance, given the current shortage of system regulation reserves.

The variability impact issue on Power System is not addressed in this paper and it will be covered in subsequent ones.

B. Dynamic simulation results

For all simulations, the following conditions were applied:

- The fault applied is a bolted symmetrical three-phase applied one second after the start of the simulation.
- The fault clearing time is 9 cycles and the simulation time is 20 seconds.

Figure 5 shows that during the fault on the 110kV connection point, the voltage drops to zero, whilst the 35 kV collector bus voltage drops to 0.12 pu. After fault clearance, the voltage at both locations gradually recovers to around 1.0 pu. The WTG terminal voltage shows a similar pattern, except that during the fault the minimum terminal voltage is 0.2 pu, which is considerably higher than the faulted connection point voltage. The range of terminal voltage drop to other 40 WTG is from 0.2 pu to 0.23 pu, depending on location of the installed units. The WTGs closest to the 35 kV collector bus have maximal terminal voltage drop. The simulation results indicate that all 40 DFIGs have the ability to ride through the fault, which is in compliance with Wind Grid Code requirements.

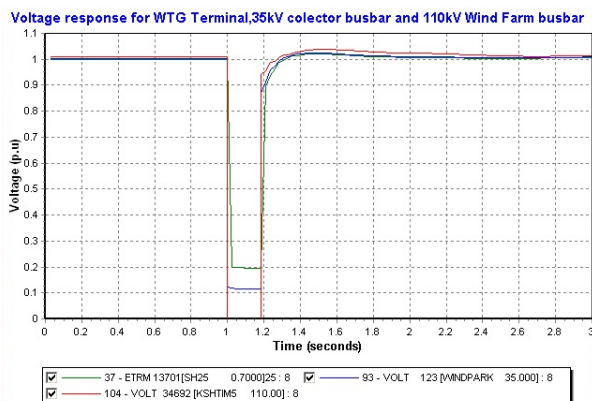


Fig.5 Voltage response after fault occur in the 110kV connection point of wind farm

Figure 6 shows WTGs terminal voltage response for three different fault events, each with different fault impedances.

The most critical case for the WTGs is when the fault occurs on the connection point to the transmission network.

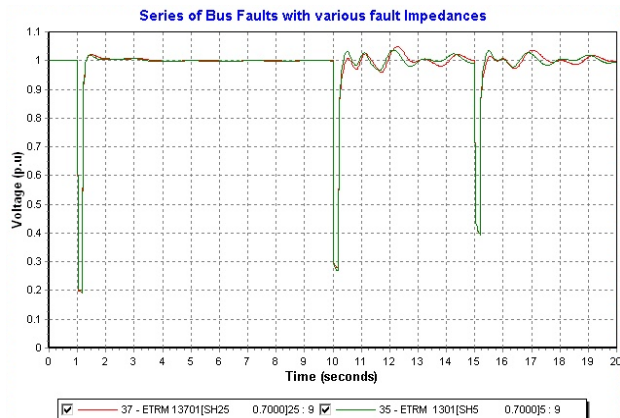


Fig.6 WTG terminal voltage response for series of Bus faults with various impedances

Figure 7 shows that during the fault the WTG electrical power output suddenly decreases to a very low value (0.001 pu or 2 kW). The difference between the mechanical input power and electrical output power causes an increase in the rotor speed and therefore the rotor starts to accelerate. The torsion oscillation in the drive-train model is reflected in the output power of the wind turbine. Oscillation of power output after the fault is cleared will cause mechanical stress in the drive train system. Approximately ten seconds after the fault is cleared, the power output recovers to the pre-fault value of 2 MW.

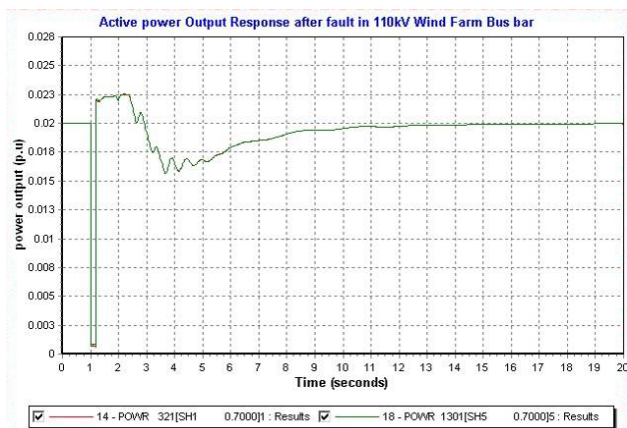


Fig.7 WTG active power response after fault

The reactive power outputs from three selected WTGs: SH1, SH4 and SH10 are shown in figure 8. Before the fault occurs, unit SH1 was compensated, unit SH4 was injecting reactive power to the grid and unit SH10 was absorbing reactive power from the grid. During the fault, the rotor speed increases, giving a larger negative slip. This is because the electric power has decreased to almost zero whereas the mechanical power is assumed to be the same. As a result, WT3P module responds by altering the blade pitch to decrease

mechanical power. During the fault we can see that all WTG units provide reactive power support to the grid, as is required by the Wind Grid Code.

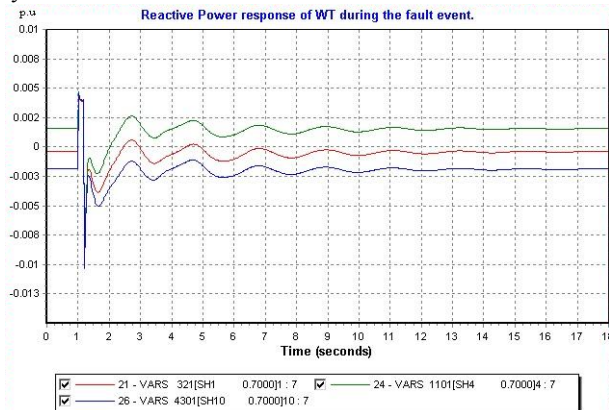


Fig.8 WTGs reactive power response for three selected units SH1, SH4 and SH10

Figure 9 shows the wind turbine shaft speed and generator rotor speed response after the fault occurs. The generator speed is oscillating, with respect to the turbine speed for about 5 seconds after the fault. 14 seconds after fault is cleared, both shaft and rotor speed recover to the pre-fault value after some 14 seconds.

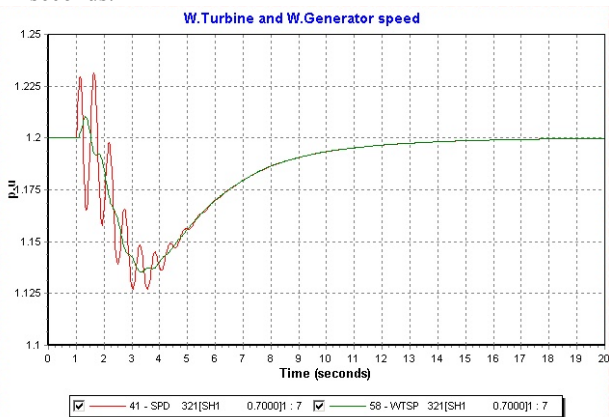


Fig.9 Wind turbine speed and generator speed response

As can be seen in figure 10, the turbine blade pitch angle is increased during the fault in order to reduce the power input from the wind turbine. The pitch angle oscillates in response to the oscillation of the speed of the turbine. For a few seconds after fault clearance, the turbine shaft speed decreases while the pitch angle increases due to the effect of pitch compensation controller trying to reduce the input power to the turbine by increasing the pitch angle.

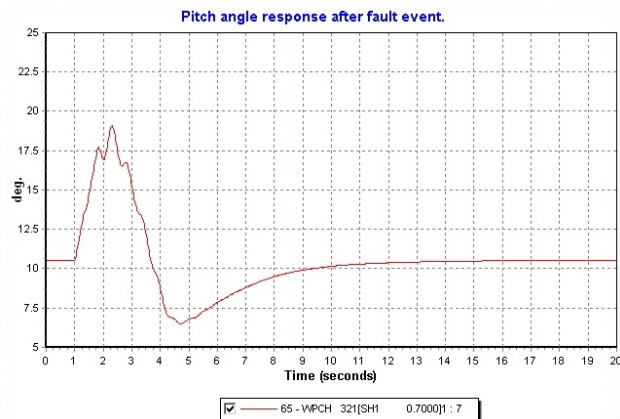


Fig.10 Pitch angle response after fault event

IV. CONCLUSION

Power flow, short circuit and dynamic analyses were carried out in order to check the influence of the 80MW wind farm on the Kosovo transmission system in respect of the Grid Code requirements. The large scale PSS/E model was used for the computer simulations. The PSS/E wind turbine stability model WT3 was used for the dynamic simulation with the objective of simulating the dynamic performance of DFIG technology WTGs. The overall conclusion of these analyses is that the 80MW wind farm project does have an influence on the transmission system, but all of the requirements of the Grid Code relating to the wind farm connection were satisfied.

ACKNOWLEDGMENT

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