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Issues of Connecting Wind Farms into Power Systems

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Abstract**—**Wind power industry is developing rapidly, more and more wind farms are being connected into power systems. Integration of large scale wind farms into power systems presents some challenges that must be addressed, such as system operation and control, system stability, and power quality. This paper describes modern wind power systems, presents requirements of wind turbine connection and discusses the possible control methods for wind turbines to meet the specifications.

Index Terms— Wind turbines, Wind farms, Power quality, Frequency and voltage control, Stability.

I. Introduction

Wind turbine technology has undergone a revolution during the last century. The attention has continued to grow as the demands on reducing polluting emissions have increased. The global wind energy sector is still developing rapidly [1, 2]. For example, EU countries plan to develop large scale offshore wind farms, 10000 MW by 2010, including an expected offshore wind power capacity of 4000 MW in the UK. The target for installed wind energy is 5500 MW in Denmark by 2030, out of which 4000 MW will be offshore.

With the development of wind turbine technology, large scale wind farms of hundreds MW level are being developed in many countries. These modern wind farms are usually connected to the power grid. The wind power penetration levels in the networks could be high, for example, average wind power penetration levels of 20-30 % with peak penetration level up to 100%. Which will effectively reduce the requirement on the fossil fuel based conventional power generation, however, it also presents many challenges to modern power systems. The issues, such as power system operation and control, system stability and power quality, need to be addressed in order to realise good security and power quality for the power systems integrating large scale wind power [3, 4, 5, 6].

Technical constraints of power generation integration in a power system may in general be associated with the thermal limit, frequency and voltage control and stability. Grid codes are set up to specify the relevant requirements, these specifications have to be met in order to integrate wind turbines into the grid.

This paper will discuses the important issues related to the large scale wind power integration into modern power systems. Firstly, the wind power generation and transmission will be described; the impacts of wind farm on power quality issue are to be analysed, then the technical requirements for wind farm grid connection will be introduced. The possible operation and control methods to meet the specifications and to improve system stability are discussed. A simulation example is also presented to illustrate a stability problem and the possible method of improving the stability.

II. Wind Power Generation and Transmission

The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. The conversion of wind power to mechanical power is done aerodynamically. The available power depends on the wind speed but it is important to be able to control and limit the power at higher wind speed to avoid damage. A turbine could be designed in such a way that it converts as much power as possible in all wind speeds, but then it would have to be too heavy. The high costs of such a design would not be compensated by the extra production in high winds, since such winds are rare. The power limitation may be done by one of the aerodynamic mechanisms as shown in Fig. 1 [7]: stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed).

Conventional power stations are usually connected to the high voltage or extra-high voltage system. While Wind turbines may be connected to ac system at various voltage levels, including the low voltage, medium voltage, high voltage as well as to the extra high voltage system. The suitable voltage level depends on the amount of power generated. For example, for large onshore wind farms at hundreds of MW level, high voltage overhead lines above 100kV are normally used. For offshore wind farms with a long distance transmission to an on shore grid, a high voltage submarine cable may have to be used. Fig. 2 sketches the electrical connection of Danish Horns Rev offshore wind farm which includes 80 wind turbines with doubly fed induction generators [8].

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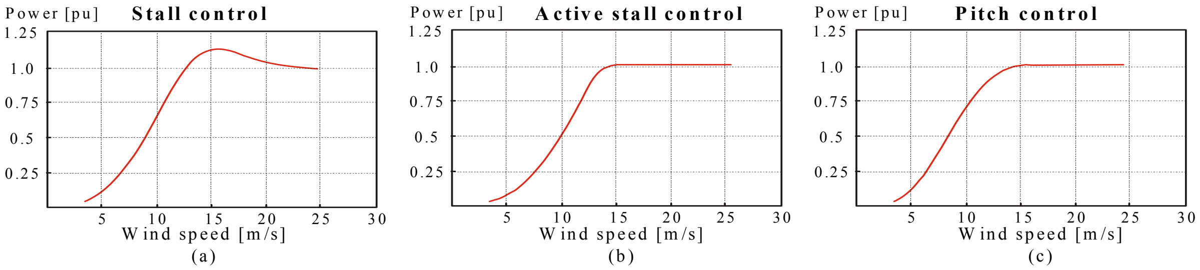

Fig. 1. Power characteristics of fixed speed wind turbines (a) stall control (b) active stall control (c) pitch control.

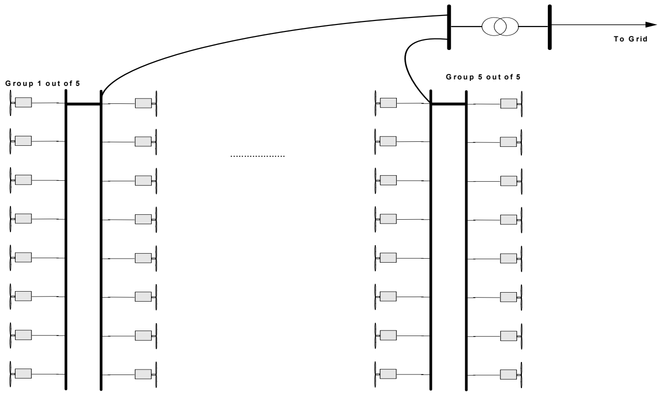

Fig. 2. Basic configurations of Horns Rov wind farm, Denmark.

Direct connecting an induction generator may result in transients, the resultant inrush current could cause disturbances to the grid and high torque spikes in the drive train. Such transient could limit the acceptable number of wind turbines, a current limiter or soft starter based on thyristor technology is used to limit the inrush current to a level below two times the rated current of the generator, which effectively dampens the torque peaks of the generator and reduces the loads on the driving train. In normal operation states, the soft starter is bypassed by a short circuited contactor to reduce the power loss associated with the semiconductors and reduce the required thermal capacity of the soft starter. For full rated power electronic interfaced induction generators, the current can be controlled continuously from zero to rated current, the disturbances to the grid during switching operations are minimized.

A modern wind turbine is often equipped with a transformer stepping up from the generator terminal voltage, usually a voltage below 1 kV, to a medium voltage at around 20 kV or 30 kV, for ac system connection.

The grid connection may include two parts, the local electrical connection within a wind farm at a medium voltage level and the connection from the wind farm to the electrical grid. If the wind farm is large and the distance to the grid is long, a transformer is used to step up the medium voltage in the wind farm to the high voltage at transmission level.

Submarine cables with a lead sheath and steel amour are used for connecting an offshore wind farm to a on shore grid, either oil-insulated cables or PEX-insulated cables can be used. The reactive power produced by the submarine cable of connecting an offshore wind farm could be very high, a 40 km long cable at 150 kV would produce around 100 Mvar [9], reactors will be needed to compensate the reactive power produced by the cable.

For long distance transmission, the transmission capacity of cables may be mainly occupied by the produced reactive power, therefore ac transmission will meet difficulties. In this situation high voltage direct current (HVDC) transmission techniques may be used. The new technology, voltage source converter based HVDC system, provides new possibilities for performing voltage regulation and improving dynamic stability of the wind farm as it will be possible to control the reactive power of the wind farm and perhaps keep the voltage during the faults clearance and fast reclosures in the onshore transmission system.

III. Impacts of Wind Farms on Power Quality

A. Voltage variations

On the local level, voltage variations are the main problem associated with wind power. This can be the limiting factor on the amount of wind power which can be installed.

In normal operational condition, the voltage quality of a wind turbine or a group of wind turbines may be assessed in terms of the following parameters [10]:

- Steady state voltage under continuous production of power
- Voltage fluctuations
  - Flicker during operation
  - Flicker due to switching

The influence of connecting a wind farm on the gird voltage is directly related to the short circuit power level. The short circuit power level in a given point in the electrical network represents the system strength. If the voltage at a remote point can be taken as constant, U_s, and the short circuit power level S_{SC} in MVA is defined as U_s^2 / Z_k where Z_k is the equivalent impedance between the points concerned.

Fig. 3 illustrates an equivalent wind power generation unit, connected to a network with equivalent short circuit impedance, Z_k. The network voltage at the assumed infinite busbar and the voltage at the Point of Common Coupling (PCC) are U_s and U_g, respectively. The output power and reactive power of the generation unit are P_g and Q_g, which corresponds to a current I_g.

$$I_g = \left(S_g / U_g\right)^* = \frac{P_g - jQ_g}{U_s} \tag{1}$$

The voltage difference, ΔU, between the system and the connection point is given by

$$U_g - U_s = \Delta U = Z_k I_g = (R_k + jX_k)\left(\frac{P_g - jQ_g}{U_g}\right) \tag{2}$$

$$= \frac{R_k P_g + X_k Q_g}{U_g} + j\frac{P_g X_k - Q_g R_k}{U_g} = \Delta U_p + j\Delta U_q$$

The voltage difference, ΔU, is related to the short circuit impedance, the real and reactive power output of the wind power generation unit. It is clear that the variations of the generated power will result in the variations of the voltage at PCC. If the impedance Z_k is small then the voltage variations will be small (the grid is strong). On the other hand, if Z_k is large, then the voltage variations will be large (the grid is weak). However, strong or weak are relative concepts. For a given wind power capacity P the ratio $R_{SC} = S_{SC} / P$ is a measure of the strength. The grid may be considered as strong with respect to the wind farm installation if R_{SC} is above 20.

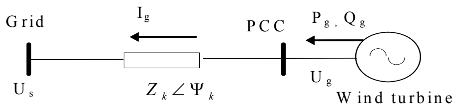

Fig 3. A simple system with an equivalent wind power generator connected to a network.

B. Steady-state voltage

Equation (2) indicates the relationship between the voltage and power transferred into the system. The voltage difference, ΔU, can be calculated with load flow methods as well as other simulation techniques [11]. The voltage at PCC should be maintained within utility regulatory limits. Operation of wind turbines may affect the voltage in the connected network. If necessary, the appropriate methods should be taken to ensure that the wind turbine installation does not bring the magnitude of the voltage outside the required limits.

It is recommended that load-flow analyses be conducted to assess this effect to ensure that the wind turbine installation does not bring the magnitude of the voltage outside the required limits.

Depending on the scope of the load-flow analysis, a wind turbine installation may be assumed as a PQ node, which may use ten minutes average data (P_{mc} and Q_{mc}) or 60 s average data (P_{60} and Q_{60}) or 0.2 s average data ($P_{0.2}$ and $Q_{0.2}$).

A wind farm with multiple wind turbines may be represented with its output power at the PCC. Ten minute average data (P_{mc} and Q_{mc}) and 60 s average data (P_{60} and Q_{60}) can be calculated by simple summation of the output from each wind turbine, whereas 0.2 s average data ($P_{0.2}$ and $Q_{0.2}$) may be calculated according to equations (3) and (4) below.

$$P_{0.2\Sigma} = \sum_{i=1}^{N_{wt}} P_{n,i} + \sqrt{\sum_{i=1}^{N_{wt}} \left(P_{0.2,i} - P_{n,i}\right)^2} \tag{3}$$

$$Q_{0.2\Sigma} = \sum_{i=1}^{N_{wt}} Q_{n,i} + \sqrt{\sum_{i=1}^{N_{wt}} \left(Q_{0.2,i} - Q_{n,i}\right)^2} \tag{4}$$

where $P_{n,i}$, $Q_{n,i}$ are the rated real and reactive power of the individual wind turbine; N_{wt} is the number of wind turbines in the group.

C. Voltage fluctuations

Fluctuations in the system voltage (more specifically in its rms value) may cause perceptible light flicker depending on the magnitude and frequency of the fluctuation. This type of disturbance is called voltage flicker, or shortened as flicker.

There are two types of flicker emissions associated with wind turbines, the flicker emission during continuous operation and the flicker emission due to generator and capacitor switchings. Often, one or the other will be predominant. The allowable flicker limits are generally established by individual utilities. Rapid variations in the power output from a wind turbine, such as generator switching and capacitor switching, can also result in variations in the RMS value of the voltage. At certain rate and magnitude, the variations cause flickering of the electric light. In order to prevent flicker emission from impairing the voltage quality, the operation of the generation units should not cause excessive voltage flicker.

IEC 61000-4-15 specifies a flickermeter which can be used to measure flicker directly [12]. The flicker measurement is based on the measurements of three instantaneous phase voltages and currents followed by using a "flicker algorithm" to calculate the P_{st} and P_{lt}. where P_{st} is the short term flicker severity factor and measured over 10 minutes, and the long term flicker severity factor P_{lt} is defined for two hour periods. The flicker assessments can also be conducted with simulation method [13].

Disturbances just visible are said to have a flicker severity factor of $P_{st} = 1$ The flicker emissions, P_{st} and P_{lt} may also be estimated with the coefficient and factors, $c_f(\Psi_k, v_a)$ and $k_f(\Psi_k)$ obtained from the measurements, which are usually provided by wind turbine manufacturers.

The flicker emissions from a wind turbine installation should be limited to comply with the flicker emission limits. It is recommended [3] that $P_{lt} \leq 0.50$ in 10-20 kV networks and $P_{lt} \leq 0.35$ in 50-60 kV networks are considered acceptable. However, different utilities may have different flicker emission limits. The assessments of the flicker emissions are described below.

1) Continuous operation

The flicker emission from a single wind turbine during continuous operation may be estimated by:

$$P_{st} = c_f(\psi_k, v_a)\frac{S_n}{S_k} \quad (5)$$

Where $c_f\ (\Psi_k, v_a)$ is the flicker coefficient of the wind turbine for the given network impedance phase angle, Ψ_k, at the PCC, and for the given annual average wind speed, v_a, at hub-height of the wind turbine.

A table of data produced from the measurements at a number of specified impedance angles and wind speeds can be provided by wind turbine manufactures. From the table, the flicker coefficient of the wind turbine for the actual Ψ_k and v_a at the site may be found by applying linear interpolation.

The flicker emission from a group of wind turbines connected to the PCC is estimated using equation (6)

$$P_{st\Sigma} = \frac{1}{S_k}\sqrt{\sum_{i=1}^{N_{wt}}\left(c_{f,i}(\psi_k, v_a)S_{n,i}\right)^2} \quad (6)$$

Where $c_{f,i}\ (\Psi_k, v_a)$ is the flicker coefficient of the individual wind turbine; $S_{n,i}$ is the rated apparent power of the individual wind turbine; N_{wt} is the number of wind turbines connected to the PCC.

If the limits of the flicker emission are known, the maximum allowable number of wind turbines for connection can be determined.

2) Switching operations

The flicker emission due to switching operations of a single wind turbine can be calculated as

$$P_{st} = 18 \times N_{10}^{0.31} \times k_f(\psi_k)\frac{S_n}{S_k} \quad (7)$$

where $k_f(\Psi_k)$ is the flicker step factor of the wind turbine for the given Ψ_k at the PCC.

The flicker step factor of the wind turbine for the actual Ψ_k at the site may be found by applying linear interpolation to the table of data produced from the measurements by wind turbine manufacturers.

The flicker emission from a group of wind turbines connected to the PCC can be estimated from:

$$P_{st\Sigma} = \frac{18}{S_k}\left(\sum_{i=1}^{N_{wt}} N_{10,i}\left(k_{f,i}(\psi_k)S_{n,i}\right)^{3.2}\right)^{0.31} \quad (8)$$

Where $k_{f,i}\ (\Psi_k)$ is the flicker step factor of the individual wind turbine; $N_{10,i}$ and $N_{120,i}$ are the number of switching operations of the individual wind turbine within 10 minute and 2 hour period respectively. $S_{n,i}$is the rated apparent power of the individual wind turbine;

Again, if the limits of the flicker emission are given, the maximum allowable number of switching operations in a specified period, or the maximum permissible flicker emission factor, or the required short circuit capacity at the PCC may be determined.

D. Harmonics

Harmonic disturbances are a phenomenon associated with the distortion of the fundamental sine wave and are produced by non-linearity of electrical equipment. Harmonics causes increased currents, power losses and possible destructive overheating in equipment. Harmonics may also rise problems in communication circuits. Harmonic standards are specified to set up the limits on the Total Harmonic Distortion (THD) as well as on the individual harmonics.

Power electronic converters, which operation in an on-and-off way, are used in variable speed wind turbine systems [14, 15]. The Pulse Width Modulation (PWM) switching frequency, with a typical switching frequency of a few thousand Hz, shifts the harmonics to higher frequencies where the harmonics can be easily removed by smaller filters. In general harmonic standards can be met by modern wind turbines.

IV. Requirements of Connecting Wind Farm into Power Systems

Integration of large scale wind power may have severe impacts on the power system operation. Traditionally, wind turbines are not required to participate in frequency and voltage control. However, in recent years, attention has been increased on wind farm performance in power systems. Consequently, some grid codes have been defined to specify the steady and dynamic requirements that wind turbines must meet in order to be connected to the grid. Examples on such requirements are capabilities of contributing to frequency and voltage control by continuous modulation of active power and reactive power supplied to the transmission system, as well as the power regulation rate that a wind farm must provide.

Some specifications have been worked out with regard to the preparations for future large offshore wind farms as the following example [3].

- Active power and frequency control: the active power is regulated linearly with frequency variation between a certain range (47 Hz -52 Hz) with a dead band (49.85 Hz -50.15 Hz) and the regulating speed is 10 % of the rated power per second,
- The reactive power should be regulated within a control band, at a maximum level of 10% of rated power (absorption at zero real power and production at the rated real power),
- Wind turbine will generally operate in normal conditions (90%-105% voltage and 49-51 Hz), however, it should also be able to operate outside of the above conditions within certain specified time limits,
- Under the condition of a power system fault, a wind turbine would experience a voltage variation. The severer degree of the voltage variation and the time period of such voltage variation will determine whether the wind turbine must not be disconnected (ride through) or may be disconnected or must be disconnected.
- Also the wind turbine has to be able to withstand more than one independent faults occurred in a few minute intervals.

There are also requirements related to rapid voltage variations, flickers, harmonics and interharmonics.

A series of special test conditions have been set and the wind turbines have to meet these conditions accordingly before they can be connected into the power system. the regulation ability of reducing the wind turbine production from full load to a level between 0 and 20 per cent in a few seconds is required.

V. WIND FARMS OPERATION AND CONTROL, STABILITY IMPROMENT

A lot research has been conducted in answering the challenges [16-27]. In this section, some possible methods of dealing with the above requirements are discussed.

A. Frequency and power control

The real power generation of a wind turbine can be regulated down but it may be difficult to increase the power output since the input power is limited by the wind speed. However, some spinning reserve may be kept if the wind turbine is operated at a lower power level than the available power level which means a reduction in generation, and hence reduced revenues.

Large scale energy storage system may present an answer, some fast response energy storage devices could be well technically suited for this purpose though more work is needed to make the solution an economic one [16]. From the system operator's point view, a system level hot reserve allocation amount the generation units may be more cost effective to deal with the problem if possible.

B. Reactive power compensation

Many wind turbines are equipped with induction generators which consume reactive power. At no load (idling), the reactive power consumption is about 35-40% of the rated active power, and increases to around 60% at rated power. Reactive power is one of the major causes of voltage instability in the network due to the associated voltage drops in the transmission lines, reactive current also contributes to system losses.

Locally installed capacitor banks may compensate the reactive power demand of the induction generators. For WT with self commutated power electronic systems, the reactive power can be controlled to minimize losses and to increase voltage stability. Thus these WT can have a power factor of 1.00, as well as have the possibility to control voltage by controlling the reactive power. For a large scale wind farm, a central reactive power compensation device, such as SVC or STATCOM may be used to provide a smooth reactive power regulation [16].

C. Stability support

An important issue when integrating large scale wind farms is the impacts on the system stability and transient behavior.

System stability is largely associated with power system faults in a network such as tripping of transmission lines, loss of production capacity (generator unit failure) and short circuits. These failures disrupt the balance of power (active and reactive) and change the power flow. Though the capacity of the operating generators may be adequate, large voltage drops may occur suddenly. The unbalance and re-distribution of real and reactive power in the network may force the voltage to vary beyond the boundary of stability. A period of low voltage (brownout) may occur and possibly be followed by a complete loss of power (blackout).

Many of power system faults are cleared by the relay protection of the transmission system either by disconnection or by disconnection and fast reclosure. In all the situations the result is a short period with low or no voltage followed by a period when the voltage returns. A wind farm nearby will see this event. In early days of the development of wind energy, only a few wind turbines were connected to the grid. In this situation, when a fault somewhere in the lines caused the voltage at the wind turbine to drop, the wind turbine was simply disconnected from the grid and was reconnected when the fault was cleared and the voltage returned to normal. Because the penetration of wind power in the early days was low, the sudden disconnection of a wind turbine or even a wind farm from the grid did not cause a significant impact on the stability of the power system. With the increasing penetration of wind energy, the contribution of power generated by a wind farm can be significant. If the entire wind farm is suddenly disconnected at full generation, the system will loss further production capability. Unless the remaining operating power plants have enough "spinning reserve", to replace the loss within very short time, a large frequency and voltage drop will occur and possibly followed by complete loss of power. Therefore, the new generation of wind turbines is required to be able to "ride through" during disturbances and faults to avoid total disconnection from the grid.

In order to keep system stability, it is necessary to ensure that the wind turbine restores normal operation in an appropriate way and within appropriate time. This could have different focuses in different types of wind turbine technologies, and may include supporting the system voltage with reactive power compensation devices, such as interface power electronics, SVC, STATCOM and keeping the generator at appropriate speed by regulating the power etc. [22-27].

VI. A SIMULATION EXAMPLE

The studied system is shown in Fig. 4 [27], where the load at bus 2 is supplied by the grid and the wind farm with wound rotor induction generators represented by a single machine at bus 3. The capacitor DC link for STATCOM is simplified as a constant dc voltage source. It is also assumed that the switching duty ratio of the power devices connected in the rotor circuit is kept constant during the dynamics.

A three-phase short-circuit fault occurs on the middle of one of the two parallel lines. It begins at 2 s and the line is tripped after 150 ms. The voltage at the wind turbine drops during the fault period, which leads to a reduction in the electromagnetic torque and acceleration of the rotor. The pitch angle control is in emergency operation to limit the input power during the power system fault. The results with and without the STATCOM in operation are respectively presented in Fig. 5 and Fig. 6. In Fig. 5, it can be clearly seen that the generator terminal voltage can not recovered after the fault and the generator will be tripped by the over-speed protection. In Fig. 6, the STATCOM effectively restored the generator terminal voltage and the system will restore normal operation. It can be seen that the STATCOM control is an effective way to improve system stability in this case.

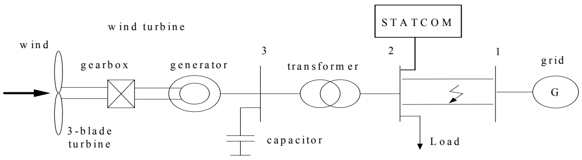

Fig. 4. Block diagram of a wind turbine connected to a grid.

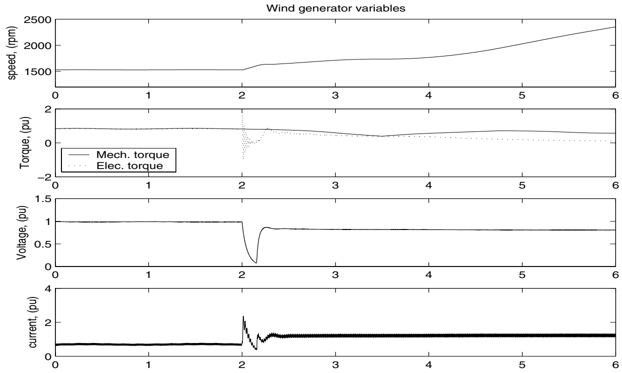

Fig. 5. Simulation results with pitch control but without STATCOM.

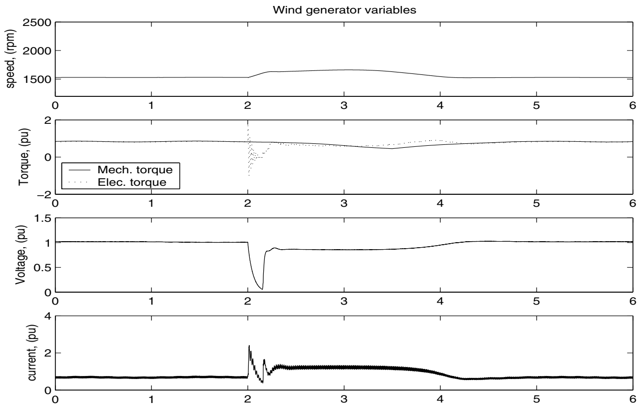

Fig. 6. Simulation results with pitch control and STATCOM.

VII. Conclusions

Integration of large scale wind power into power systems present many new challenges. This paper presents the impacts of wind power on power quality, the gird requirements for integration of wind turbines, and discusses the potential operation and control methods to meet the challenges.

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IX. Biographies

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