Impact of Wind Power Plants on Voltage Control of Power System

Sarkar, Moumita; Altin, Müfit; Hansen, Anca Daniela; Sørensen, Poul Ejnar

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Impact of Wind Power Plants on Voltage Control of Power System

Moumita Sarkar*, Müfit Altin, Anca D. Hansen, Poul E. Sørensen
Department of Wind Energy
Technical University of Denmark
Risø, 4000 Roskilde, Denmark
*Email: mosar@dtu.dk

Abstract—High penetration of renewable energy sources poses numerous challenges on stability and security of power systems. Wind power plants (WPPs) of considerable size when connected to a weak grid by long transmission lines result in low short circuit ratio at the point of connection. This may result in both transient voltage fluctuations and poor steady-state voltage profile at the point of connection. In this paper, transient and steady-state voltage support from WPPs are investigated. Low voltage ride through capability of WPP is studied for two different control modes, namely, V control and Q control, during transient voltage dips. Steady-state analysis is performed for stressed system conditions. Results are validated through simulation in a detailed power system model.

I. INTRODUCTION

Penetration of Renewable Energy Sources (RES) is increasing in electrical power systems across the globe. Wind is one of the largest contributors supplying reliable and affordable energy [1]. As of 2015, approximately 4% of global energy is supplied by wind [2]. In 2016, wind energy met 10.4% of the power demand of the European Union. Wind penetration level is substantial in some European Member States like – Denmark (42%), Ireland (27%), Portugal (25%), Spain (19%), Germany (16%), UK (12.4%) [3]. With high penetration of RES, most conventional synchronous generators are being replaced by converter connected non-synchronous generators like wind turbines (WT). This makes power systems weak due to low short circuit power available and low system inertia. Weak power systems together with variability of RES generations pose various research challenges on power system stability and security. One such challenge being voltage stability, particularly when a large WPP is connected to the grid through a long transmission line.

Variability of wind speed causes changes in active power output of WPP. This may lead to changes in reactive power output and consequently voltage at the Point of Connection (PoC). Support from WPPs may be beneficial and required to deal with system contingencies as well as normal operation of power system. Most Transmission System Operators (TSO) specify reactive power requirements for both transient and steady-state conditions for WPPs in order to be connected to their respective grid. As per Danish grid code specified by Danish TSO Energinet, WPPs are required to fulfill low voltage ride through (LVRT) and inject reactive current to support voltage dip at PoC during transient conditions [4]. During steady-state operation, three different modes of reactive power and voltage control functions from WPPs are possible namely, reactive power control, voltage control and power factor control. These three control modes are mutually exclusive and the requirements are specified in the grid code.

Modern variable-speed controllable WTs can be of two types – doubly fed induction generator (DFIG) based WTs (referred as Type 3 WTs) and fully rated converter based WTs (referred as Type 4). Type 4 WTs are only considered in this paper. Fully rated converter decouples WT generator from the grid as well as enables independent active and reactive power control. Independent reactive power support from Type 4 WTs can help in LVRT support [5]. Additionally, converters can provide very fast response which might be crucial in a low inertia, low short circuit power system [6].

At steady-state, reactive power available from WPPs depend on the active power generated. Grid code requirements as specified by TSOs are minimum requirements that the WPP has to fulfill in order to connect to the grid. Depending on WT technology, WPPs may be able to deliver additional reactive power [7]. Since individual WT’s attempt to control voltage at individual connection points can lead to instability issues, coordinated voltage control at WPP level can be helpful [8]. Centralised WPP control can also be useful in this direction as suggested by Hansen et. al. [9]. There are other centralised and decentralised WPP level control strategies also available [10].

In this paper, Type 4 WT model as described in IEC 61400-27-1 [11] has been developed and extended to account for aerodynamic behaviour due to variation in wind speed. Performance of the extended model is illustrated for changes in wind speed and reactive power setpoint. Transient as well as steady-state studies are performed on the extended model connected to a power system grid model.

Organisation of this paper is as follows: Section II describes the extended WT model and illustrates its performance. Section III illustrates transient and steady-state simulation studies performed. Section IV concludes the paper.

II. WIND TURBINE MODEL

A. IEC Model

Generic IEC 61400-27-1 WT models have been developed by International Electrotechnical Commission (IEC) [11] for short term stability studies. These models are used to simulate typical WT response during dynamic power system events [14]. Based on speed and power control methodologies, WT generator configurations are classified into four categories [12]:
1) **Type 1** represent fixed-speed WTs that are directly connected to the grid. For these type of WTs, squirrel cage induction generator (SCIG) are typically used.

2) **Type 2** represent variable-speed WTs directly connected to the grid. Typically wound rotor induction generator (WRIG) with an additional variable rotor resistance is used in these type of configurations. These variable rotor resistances allow control of slip and power output of the generators.

3) **Type 3** represent variable speed WTs with DFIGs. In this type, stator is directly connected to the grid whereas the rotor is connected to the grid via back-to-back power electronic converter.

4) **Type 4** represent variable speed WTs connected to the grid by back-to-back full scale power electronic converters. The full scale converters decouple generator from the grid. Type 4 WTs can have permanent magnet synchronous generator (PMSG), wound rotor synchronous generator (WRSG) or WRIG, connected to the rotor shaft with or without gearbox.

IEC 61400-27-1 describes modular structure for all four WT configurations. Generic modular structure of WTs consists of the following blocks: aerodynamic, mechanical, generator, electrical equipment, grid protection and control. Two types of Type 4 WT model has been specified in IEC 61400-27-1:

1) **Type 4A** configuration neglects aerodynamic and mechanical blocks of the generic WT modular structure.

2) **Type 4B** configuration includes a 2-mass mechanical model but neglects the aerodynamic block.

In this work, Type 4B WT configuration has been used.

For short term stability studies, wind speed can be assumed constant. However for long term stability analysis, variability of wind speed needs to be considered. Type 4B IEC model have been extended by Hansen et.al. [13] to include aerodynamic behaviour of rotor, such that the impact of wind speed variability can be assessed.

### B. Extended Type 4B IEC Model – inclusion of aerodynamic block

The extended model consists of a wind speed block, pitch controller, aerodynamic block and Maximum Power Point Tracking (MPPT) in addition to mechanical, active power control, reactive power control and static generator block as specified in IEC Type 4B model structure. Fig. 1 shows structure of the extended IEC model. This model can also capture the dynamic behaviour of WTs when there is change in active power setpoint. The wind farm controller interface shown in Fig. 1 depicts that the WT model can recieve input signals (like active and reactive power setpoints, overproduction requirement signal, etc) from WPP controller. Different blocks of the model will be illustrated in the following subsections.

1) **Pitch control block**: It is needed to limit the active power output from WT at rated power output during high wind speed conditions [15]. During low wind speed conditions, pitch angle remains constant at optimal pitch angle value. The block diagram of the pitch controller is shown in Fig. 2. The pitch controller consists of an antiwind-up PI controller and a servomechanism with pitch angle limitation and rate of change of angle limitation [13]. The PI controller uses the error between the actual and reference generator speed to determine the reference pitch angle. When nominal generator speed is reached, rotor speed is limited by the pitch control block by increasing pitch angle.

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**Fig. 1: Extended Type 4B IEC Model [13]**

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**Fig. 2: Pitch control block**
2) Aerodynamic block: It computes aerodynamic power output of the WT based on wind speed and pitch angle. The relation determining aerodynamic power extracted from wind [15] is given by (1).

\[ P_{aero} = \frac{1}{2} \rho \pi R^2 U^3 C_p(\lambda, \theta) \]  

where, 
- \( \rho \) = air density in kg/m\(^3\) 
- \( R \) = rotor diameter in m 
- \( U \) = wind speed in m/s 
- \( \theta \) = pitch angle 
- \( \lambda \) = tip-speed ratio 
- \( C_p \) = power coefficient

Tip-speed ratio, \( \lambda \), is defined as ratio of speed of tip of blade to wind speed and is illustrated in (2)

\[ \lambda = \frac{\omega_{rot} R}{U} \]  

where \( \omega_{rot} \) is rotor speed. Power coefficient, \( C_p \), is function of tip-speed ratio and pitch angle. It illustrates change of aerodynamic power depending on wind speed and pitch angle. \( C_p \) is modelled as a two dimensional look-up table.

3) Mechanical block: A two mass mechanical model as proposed in IEC 61400-27-1 is used. Block diagram of the mechanical model [14] is shown in Fig. 3. The two mass model is capable of capturing oscillations induced by wind gusts and change in active power setpoints which causes imbalance of electrical and mechanical torque. Stiffness \( k_{sh} \) and damping \( c_{sh} \) of shaft as well as inertia of WT rotor \( H_{rot} \) and inertia of generator \( H_{gen} \) are considered in the model. Airgap power \( P_{airgap} \) is measured as the electrical power output of the static generator.

4) MPPT table: MPPT is implemented as a lookup table which determines reference power output of generator as a function of generator speed. This table ensures that optimal aerodynamic power is being extracted by keeping the turbine working at maximum power coefficient \( C_p \), until nominal rotational speed is reached [16].

5) Active power(P) control block: P control block implemented here differs from the P control block described in IEC model. The P control block implementation is shown in Fig. 4. A low pass measurement filter is used to filter high frequency fluctuations in measured active power, \( P_{meas} \). The error signal between reference and measured active power is then passed through an anti-windup PI controller to obtain reference active current signal, \( I_{pcmd} \).

6) Reactive power(Q) control block: The Q control block implemented is similar to that illustrated for IEC Type 4B WT model. It is illustrated in Fig. 5. Different types of Q control modes can be implemented using this block: voltage control, reactive power control, power factor control, open/closed loop control. The reference signal to the Q control block can be voltage, reactive power or power factor setpoint. A low pass measurement filter is used to filter high frequency fluctuations in measured voltage or reactive power signal. Based on the chosen Q control mode, reference and measured signal are chosen. Error between measured and reference signal are then passed through an anti-windup PI controller to generate \( I_{qbase} \) signal. When voltage at PoC drops below threshold voltage due to sudden system disturbances, Q controller switches to LVRT mode. In LVRT mode, more reactive power support from WT is required to support the PoC voltage. A voltage scaling factor is used to determine the voltage dependent reactive current during LVRT, \( I_{qfault} \). Some grid codes require to inject post-fault reactive power for a specified time period. This is determined by the post-fault current contribution block and is referred here as \( I_{qpost} \). In IEC Q control block, there are provision for three different types reactive current injection during fault and in post-fault period:

- voltage dependent reactive current during fault
- pre-fault reactive current value + voltage dependent reactive current during fault
- pre-fault reactive current value + voltage dependent reactive current during fault and pre-fault reactive current value + additional constant reactive current post-fault

During normal operation, \( I_{qcmd} \) equals to \( I_{qbase} \). During fault, \( I_{qcmd} \) equals to \( I_{qfault} \) which is calculated as per the chosen LVRT current injection mode. In post-fault period, if post-fault reactive power injection is required, \( I_{qcmd} \) is set to sum of \( I_{qpost} \) and \( I_{qbase} \) else it is set to \( I_{qbase} \).

7) Static generator block: It consists of generator reference current limiter model, phase locked loop (PLL) and static generator block. Fig. 6 illustrates the block. The
static generator is used as a current source here, hence the reference active and reactive current input together with the phase information provided by the PLL is used as input to the static generator.

C. Performance of Extended Type 4B IEC Model

To evaluate model performance, a simple two bus system as shown in Fig. 7 is used. The test system includes a 2 MW Type 4 WT connected to grid through step up transformer and transmission line. Aim of these performance studies are to show that the extended IEC Type 4B model can respond to wind speed variability. Also different modes of Q control, namely, voltage control and reactive power control are evaluated here. For these purposes, the following two simulation studies are done:

- Step changes in wind speed are applied
- Step changes in reactive power setpoint are applied

Results of simulation studies are illustrated in following subsections.

1) Case 1 – step changes in wind speed: To illustrate performance of the model for varying wind speeds, step changes in wind speed are applied from 6m/s to 18m/s in steps of 1m/s every 30s. Results of the simulation – wind speed, pitch angle, generator speed and active power are shown in Fig. 8. Step changes in wind results in changes in pitch angle, generator speed and active power output from WT. It can be observed that below rated wind speed of 12m/s, pitch angle does not change. When wind speed reaches rated speed, pitching of blades start in order to limit rotor speed as generator speed limit is reached. As wind speed increases above rated speed, pitch angle increases to limit the power output. When wind speed reaches rated speed, pitching of blades start in order to limit rotor speed as generator speed limit is reached. As wind speed increases above rated speed, pitch angle increases to limit the power output. It can be observed that, generator speed increases in steps until rated generator speed is reached at rated wind speed. Above rated wind speed, generator speed remains constant at 1 p.u. Active power output from WT increases from about 0.2 pu at 6m/s to 1 p.u. at 12 m/s. Beyond rated wind speed, active power output is maintained constant at 1 p.u.

2) Case 2 – step changes in reactive power setpoint: To demonstrate output of Q controller block, step changes of 0.1 p.u. in reactive power setpoint are performed at intervals of 20s. In this case, Q controller response for two different modes of reactive power control – Q control and V control – are studied. Wind speed is kept constant at 13 m/s. Fig. 9 shows the voltage at PoC, generator speed, active power output and reactive power output of WT when operated in Q control mode. It can be seen from Fig. 9, reactive power output follows the reactive power setpoint until maximum or minimum limit of the controller is reached. Voltage at PoC changes according to reactive power output of WT. Active power output remains constant since it is not affected by
change in reactive power output. Active and reactive power can be controlled independently. Fig. 10 shows voltage at PoC, generator speed, active power output and reactive power output of WT when operated in V control mode. In this mode, the Q controller follows the voltage setpoint and tries to maintain the PoC voltage at set reference value. Reactive power reference setpoint is not considered.

These studies show that relation between pitch angle and generator speed with variation in wind speed can be simulated using the extended IEC model. These studies also illustrate operation of the reactive power controller in two different modes – V control and Q control. It can be observed that steady-state limits of the pitch, active and reactive power controller can be captured in order to perform long-term stability studies.

III. System Studies

System studies are done using the extended IEC Type 4B model connected to a detailed network. Transient performance of the model is evaluated when a three-phase fault occurs in the grid. Steady-state performance of the model is evaluated for stressed system condition when a line has been disconnected due to a permanent fault.

A. Simulation System

The wind power grid model as shown in Fig. 11 is modelled in DgSILENT PowerFactory for simulation studies. This reduced but realistic grid model was proposed by Akhmatov et. al. in [17], [18] for voltage stability studies. The system consists of 4 central power plants and an aggregated model of WPP of 300MW. The WPP comprises of extended Type 4B WT model as discussed in the Section II-B. The WPP is connected to grid at bus 111 by a 150 km long transmission line. The short circuit ratio (SCR) as defined by Gavrilovic in [19] is calculated at bus 115 which is the PoC. It is obtained as 1.52. As per IEEE guidelines for AC/DC systems [20], a system with SCR less than 2 can be defined as very weak system. Thus the bus 111 highlighted in grey in Fig. 11 is a weak bus prone to voltage fluctuations. Both dynamic and steady-state studies are performed on the system for a three-phase bolted fault at line L1 connecting bus 111 to bus 108. Line L1 is opened to clear the fault.

B. Grid Code Requirements

For these simulation studies, limits of voltage and reactive current output from WPP are set according to the Danish grid code requirements specified in [4]. For abnormal operating conditions with transient voltage dip due to system faults, voltage dip tolerance requirement and reactive current injection requirement are illustrated in Fig. 12 and Fig 13 respectively. During LVRT, delivery of reactive power is given higher priority than active power. During voltage dips, WPP must be capable of providing reactive current as shown.
in Fig. 13 within 100ms. If voltage drops below 0.5 p.u., WPP is required to deliver reactive current equal to 100% of its nominal current. WPP is required to withstand voltage dips of 20% at PoC and stay connected to the grid for 0.5s as shown in Fig. 12. If operating point moves in Area C shown in Fig. 12, WPP is allowed to disconnect.

For steady-state operations, grid code requirement of reactive power in relation to active power and normal operating voltage are illustrated in Fig. 14 and Fig. 15 respectively. Operating point of WPP for delivery of reactive power must lie in the shaded region. It can be observed from Fig. 14 that the reactive power requirement from WPP varies with active power delivered by the WPP. Between 0.2 p.u. and 0.8 p.u. of active power, maximum reactive power requirement lies between ± 0.33 p.u. Between 0.8 p.u. and 1 p.u. of active power, reactive power requirement decreases from ± 0.33 p.u. to ± 0.228 p.u. Fig. 15 shows delivery of reactive power is required between 0.9 p.u. and 1.06 p.u. of normal operating voltage.

C. Case Studies

1) Dynamic Analysis – Low Voltage Ride Through: In this case study, LVRT capability of the WPP is studied for V and Q control modes. A three-phase fault occurs on line L1 at \( t = 5 \) s. The voltage at PoC, reactive current reference set by the Q controller and the reactive power output of WPP without LVRT and with LVRT – for V control and Q control modes – are shown in Fig. 16. When there is no LVRT support from WPP, there is no priority of reactive power delivery during voltage dips. Reactive current reference remains same as pre-fault value. Due to less reactive power support from WPP, voltage at PoC drops to 0.3 p.u. during fault. When the fault is cleared at 5.1s, voltage increases to only 0.6 p.u. At 6.1s, PoC voltage reaches 0.9 p.u. This long time required for post-fault voltage recovery can cause problems in a stressed system. With LVRT support, post-fault voltage recovery is faster. Also the voltage dip during fault is less. For both V control and Q control modes, voltage at PoC drops to 0.4 p.u. during fault. When voltage at PCC drops, LVRT mode of Q controller is activated and it sets reactive current reference to 1 p.u. During fault, reactive power output from WPP increases to 0.53 p.u. At \( t = 5.1 \) s when the fault is cleared, Q controller resumes normal operation and reactive power output of WPP reduces. PoC voltage recovers to normal operating levels within 0.1s. Since post-fault system configuration has changed due to opening of line L1, post fault PoC voltage is lower than the pre-fault value for both control modes. Post-fault PoC voltage in Q control mode is lower than that in V control mode as the Q controller tries to maintain the Q reference setpoint in the former mode.

It can be observed that for system with low SCR, LVRT support from WPP is needed in order to maintain voltage...
stability of the system. Both V control and Q control modes provide equal support during LVRT but steady-state voltage differs for the two cases.

2) Steady-State Analysis – Secondary Voltage Control:
Steady-state analysis of the system is done using power flow. It is assumed that wind speed remains constant at 14 m/s. In pre-fault scenario, the WPP is run in V control mode with voltage reference set to 1.04 p.u. Pre-fault load flow results at PoC, bus 111 and reactive power output from WPP are shown in Table I. After the fault when line L1 is opened, power flow results show that the voltage at bus 111 has fallen to 0.92 when the WPP is operated in local voltage control mode with voltage reference setpoint as 1.04 p.u. Reactive power output from WPP is 0.222 p.u. At wind speed of 14 m/s when active power output from WPP is 1 p.u., reactive power output is limited to 0.228 p.u. as per Danish grid code shown in Fig. 14. As limit of reactive power output is not yet reached, voltage reference setpoint can be increased further to 1.06 p.u. in post-fault scenario. This change improves the voltage at bus 111 to 0.94 p.u. Reactive power limit of WPP is reached now. Hence it shows that centralised secondary voltage control can improve the voltage profile in weak systems, such that the maximum capability of WPP can be utilised to support weak power system in stressed conditions.

<table>
<thead>
<tr>
<th>V Control</th>
<th>V ref</th>
<th>VPoC</th>
<th>Vbus</th>
<th>QWPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-fault</td>
<td>1.04</td>
<td>1.01</td>
<td>0.95</td>
<td>0.164</td>
</tr>
<tr>
<td>Post-fault</td>
<td>1.04</td>
<td>1</td>
<td>0.92</td>
<td>0.222</td>
</tr>
</tbody>
</table>

TABLE I: Steady-State power flow results

IV. CONCLUSION
LVRT support from WPPs are required in systems with low SCR. Not prioritizing reactive power delivery during faults can cause lower voltage dips at PoC. Also post-fault voltage recovery is affected. LVRT mode of operation helps in stabilising the PoC voltage faster in post-fault period. During fault, behaviour of V control and Q control modes of operation are similar. Post-fault steady-state voltage differs for the two modes. In steady-state operation, local voltage control may not be able to utilize full capability of WPP. Centralised secondary voltage control is required to improve voltage profile specially in weak systems. Further investigations are required in developing methodology for centralised secondary voltage control of WPPs.

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