Abstract: - Nowadays, technology evolution and deregulation of the electric utility industry enable Distributed Generation (DG) to play an increasing role in satisfying locally the expanding power demand and generally provide ancillary services to the system. In this paper, the capability of wind turbines (WTs) to support the frequency of the system is investigated. A control strategy depending only on local frequency measurements without the need of central control is simulated. Frequency support facility is a crucial technical characteristic for small and isolated power systems with WTs installed and also for large power systems with increased wind penetration. The above are validated with simulation results.

Key-Words: - Frequency support, modeling, variable speed wind turbines (VSWT), control.

1 Introduction
Distributed generation from renewable energy sources in MV and LV distribution networks accounts today for a small share of the overall power supplied by those networks. This level of penetration has justified current utility practices to consider distributed generators (DGs) as a negative load in their planning and operation strategies. This situation is likely to change in the near future, as a large scale installation of DGs is encouraged in many countries due to the distinct benefits they can offer regarding reliability and quality of supply, as well as increased efficiency. Also, the amounts of wind power injected directly to HV networks are generally limited not affecting considerably system dynamics yet.

Technical challenges associated with the operation and coordinated control of DGs and generally with wind power generation are immense [1]-[3]. Ensuring stable operation during network disturbances, maintaining stability and power quality in case of large wind penetration require the development of sophisticated control strategies in order to provide stable frequency and voltage in the presence of arbitrarily varying loads and wind conditions [4]-[5].

Traditionally, power grids are based on rotating masses and these are regarded essential for the inherent stability of the systems. In contrast, WTs are mostly interfaced through inverters without directly connected rotating masses. This approach is technically demanding, as the converter control must provide the response previously obtained from the directly connected rotating masses, but it does offer the possibility of more flexible operation.

This paper demonstrates a control scheme applied to VSWTs connected to power systems with large wind penetration. The aim of this control method is to alleviate frequency deviations caused by large wind power volatility. In the proposed control scheme communication and extra cabling is avoided, because the controller itself determines its instantaneous value for active power. This is achieved by applying active power/frequency droop to the VSWT. Local system frequency, wind speed measurements and available wind power estimations are used for active power set-point estimation. It is shown that the proposed control scheme achieves satisfying regulation of the frequency and generally reduces frequency deviations caused by wind power variation. Finally, the results are compared with those obtained if maximum efficiency goal is pursued.

2 System Components Modeling
There are two modes of operation of the VSWT, examined next, depending on the status of the electrical grid; namely with or without frequency support. The VSWT model used in frequency support mode of operation is described next, while the control concept employed in maximum power
2.1 Models of Aerodynamic, Mechanical and Generator systems

2.1.1 Aerodynamic system

The WT rotor aerodynamics are modeled using the well–known aerodynamic power coefficient \( C_p(\beta) \) as:

\[
P_a = \omega_r \cdot T_a = \frac{1}{2} \cdot \rho \cdot A \cdot C_p(\beta) \cdot V_w^3
\]

\( P_a \) is the aerodynamic power, \( C_p(\beta) \) is the dimensionless aerodynamic power performance coefficient, \( \lambda \) is the tip speed ratio, \( \beta \) is the pitch angle, \( \rho=1.25 \text{ kg/m}^3 \) is the air density, \( A=\pi \alpha^2 \) is the rotor swept area, \( V_w \) is the wind speed, \( \omega_r \) is the blade rotating speed and \( T_a \) is the aerodynamic torque. For the reproduction of the wind speed time series a Fourier synthesis method is applied which employs the Von Karman spectral density function of the wind turbulence [6].

2.1.2 Mechanical system

The drive train can be described to a sufficient level of accuracy by two inertias connected by a spring and damper and viscous friction on each inertia. The external forces are the aerodynamic torque, \( T_a \), on the slow speed shaft and generator torque, \( T_g \), on the high speed shaft. The mechanical equivalent of the two elastically connected masses is shown in Fig. 1.

This results in a set of differential equations, which for simplicity will be referred to via the general state space form (2), with

\[
x = \begin{bmatrix} \omega_r & \omega_g & \Delta \theta \end{bmatrix}^T
\]

\[
\begin{bmatrix}
\dot{\omega}_r \\
\dot{\omega}_g \\
\Delta \theta
\end{bmatrix} =
\begin{bmatrix}
-(d+D_g) & d & -k \\
H_r & -H_g & H_g \\
1 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
\omega_r \\
\omega_g \\
\Delta \theta
\end{bmatrix}
+ \begin{bmatrix} T_a \\
0 \\
0
\end{bmatrix}
\]

Where, \( \omega_r, \omega_g \), are rotating speeds of the blades and generator rotor, \( d, D_r, D_g \), are the damper and the viscous friction coefficients, \( k \) is elasticity stiffness coefficient, \( H_r, H_g \) are the inertias of the blades and generator rotor and \( \Delta \theta \) is the relative angular displacement of the rotating masses.

2.1.3 Electric generator and generator control system

Asynchronous generators are usually modeled by the well–known 4th order dq model [7]. If synchronous generator is used then second order model for stator dynamics neglecting damper winding effects is adequate [7].

In this study more simplified models of generator are used because the dynamics of the electric system are very fast compared with the dynamics of the mechanical system as well as system frequency dynamics. This justifies considering the electric generator as a first-order transfer function for the needs of the paper. Consequently, the rotating speed control loop in conjunction with the generator simplified model, as shown in Fig. 2, are used to model the electric generator of the VSWT.

Rotating speed is maintained close to its reference by regulating the electromagnetic torque via a classical PI controller.

Value and rate limiters are applied to \( T_{g,ref} \) in order to limit the mechanical stresses. The upper and lower limits of the electromagnetic torque reference are set to 1.1 (p.u.) and 0.05 (p.u.), respectively, while the limits of \( T_{g,ref} \) time-derivative are +/-0.2pu/sec.

\[
\begin{align*}
\omega_g & \quad \text{PI} \\
\omega_{g,ref} & \quad \frac{T_g}{T_g} \\
& \quad \frac{1}{sT_1+1} \\
& \quad T_g
\end{align*}
\]
FIG. 3 Rotating speed reference production

In the block diagram of Fig. 3 the rotating speed reference derivation is shown. The rotating speed reference is calculated from the filtered output of the wind speed – optimal rotating speed characteristic. At low wind speed, the optimal rotating speed is applied as reference, while at high wind speed a constant rotating speed is imposed according to the \( V_w - \omega_{g,ref} \) characteristic of Fig. 3. In the range of 4m/sec-9m/sec the rotating speed’s reference varies linearly between 0.4 (p.u.) and 0.9 (p.u.).

The upper limit of the rotating speed is calculated as,

\[
\hat{\omega}_{r,\text{max}} = \frac{\lambda_{opt} \hat{V}_{w,0.9}}{R}
\]

where \( \hat{V}_{w,0.9} \) is the wind speed that corresponds to output active power equal to 90% of the nominal, if operating with maximum \( C_p \). \( \lambda_{opt} \) is the optimum value of tip speed ratio, \( \lambda \). In case of wind gusts, small deviations of \( \hat{\omega}_{r,\text{max}} \) are allowed, in order to moderate mechanical stresses.

A time constant equal to 4.5sec is used for the first order transfer function. In case of inaccurate wind speed measurements, a wind speed estimator can be used e.g. a neural wind speed estimator or Kalman filter as described in [5].

2.1.4 Pitch angle control

Regarding the control system of the blades pitch angle, a simple PI controller is applied so that active power reference is achieved via pitch angle regulation.

Value and time-derivative limiters are used at the output of the PI controller. The respective limits are:

\[
\frac{d\beta^+}{dt} = 5\text{deg/s}, \frac{d\beta^-}{dt} = -5\text{deg/s}, \beta^+ = 60\text{deg}, \beta^- = 0\text{deg}
\]

2.1.5 Electric grid

Without loss of generality the model of the power system is referred to an equivalent synchronous generator for the purposes of the paper. More specifically, the motion equation of the equivalent synchronous generator is used in a suitable form taking into account an equivalent inertia and the frequency droop. In this way the frequency deviations due to the variable wind power production are reproduced.

Changes of mechanical power driving the electrical generators of the system and changes of system electric load are related with the system frequency as shown in (4).

\[
J' \cdot f \cdot \frac{d\Delta f}{dt} = \Delta P_m - \Delta P_{m_{(p.u.)}}
\]

Where, \( P_m \) is the active power produced by the generator, \( P_{m_{(p.u.)}} \) is the accelerating mechanical power, \( f \) is system frequency, \( \Delta f = 1 - f \) (p.u.), \( J' \) is the equivalent system inertia (in sec). Symbol \( \Delta \) denotes the differential change.

The analysis that follows takes into consideration primary and secondary frequency adjustment. If only the primary frequency adjustment is to be examined, the frequency droop equation of the generator is:

\[
\Delta P_m = R_f \cdot \Delta f
\]

where, \( R_f \) is frequency droop of the generator and its associated speed governor.

On the other hand, if secondary frequency adjustment is taken into account too, then (5) turns into:

\[
\Delta P_m = R_f \cdot \Delta f + K_f \cdot \int_0^T \Delta f dt
\]

With \( K_f \) being the integral gain of the speed controller.

The solution of the set of equations (4) and (6) results in frequency deviation estimation taking also into account, the secondary frequency adjustment:

\[
J' \cdot f \cdot \left( \frac{d\Delta f}{dt} - R_f \cdot \Delta f - K_f \cdot \int_0^T \Delta f dt \right)
\]

In addition, assuming that frequency is close to its nominal value, i.e. \( f \approx 1 \) (p.u.), then (7) is reduced to:

\[
J' \cdot \frac{d\Delta f}{dt} = P - R_f \cdot \Delta f - K_f \cdot \int_0^T \Delta f dt
\]

2.2 Control System of Variable Speed Wind Turbines – System Frequency Support Mode of Operation

In islanded mode of operation, the VSWTs should always provide the power demanded in order to keep frequency and voltage in the isolated part of the grid close to their nominal values (e.g. 50 Hz, 20 kV). This mode operation and the associated WT
models are studied in [4]-[5]. However, in frequency support mode of operation they are connected to the main grid but they shall arrange appropriately their produced power in order to minimize frequency deviations from its nominal value. The frequency support mode of operation is modeled next.

The conventional approach of f/P droop (R_f) is followed in this paper thus downscaling the conventional grid control concept to the VSWTs [4], [5], [8].

In more detail, the f-P characteristic form adopted by the TSO of Ireland is used next and it is shown in Fig. 5. The idea behind this curve is to provide regulation of the produced active power with regard to system frequency. The produced power is regulated to a constant fraction of the available power within a certain band of frequencies around 50Hz called as frequency dead band. In our case f_B=49.9Hz and f_C=50.1Hz. For frequencies lower than f_B the fraction of the produced power to the available one is linearly increased to 100% (f=f_A) while for frequencies greater than f_C the fraction of produced power to the maximum available is linearly decreased until frequency, f_D.

2.2.1 Frequency support logic implementation

The implementation of the f-P characteristic of Fig. 5 is given next in programming code format.

```matlab
if Frequency<f_C and Frequency>f_B
    P_ref = k_1 P_av;
else
    if Frequency>f_C
        P_ref = k_1 P_av - k_2 P_av (f - f_C) / (f_D - f_C);
    else
        P_ref = k_1 P_av + P_av - k_2 P_av (f - f_B) / (f_A - f_B);
    end
end
```

2.2.2 Advantages of the proposed method

The proposed control system presents several advantages such as, low cost, easy expansion, increased redundancy and simplified supervisory control. Furthermore, instead of measuring wind speed this can be reliably and accurately estimated as it was shown in [5]. In this way reliable estimations of the available wind power are produced in real time. Taking into consideration the accurate and fast response of power electronics there are no significant errors introduced.

A simplified block diagram of the VSWT model is shown in Fig. 6. It consists of several blocks corresponding to the different subsystems of the VSWT and the associated control functions.

In general, the concept followed in this study is to achieve rotating speed close to its optimal value while at the same time regulate the aerodynamic power captured by the blades via pitch angle control with regard to the measured frequency.

![Fig. 5 Typical frequency droop characteristics](image)

![Fig. 6 WT model layout](image)
2.3 Maximum Power Tracking Mode of Operation

In order to complete the presentation of the VSWT control system, the strategy followed in maximum power tracking mode of operation is briefly described next. The generator control system is shown in Fig. 7. At low wind speed, maximum energy efficiency is achieved by tracking the optimal rotating speed while at high wind speed the control scheme imposes a constant rotating speed and the pitch angle regulation control loop is activated in order to limit the torque and the produced power within the design values. The generator control system consists of blade’s rotating speed control loop. The input signal, which is the wind speed, is led to the wind speed–blade’s optimal rotating speed characteristic, which produces the input signal to a first order transfer function. The output of the transfer function is fed next as input to the rotating speed controller. The desired electromagnetic torque is achieved by the application of an indirect field oriented voltage control scheme [7], [9]. Because of the fast dynamics of the electrical system this is modeled with a first order transfer function with suitable time constant. The same value and rate limits for $\beta$, $T_g$, used in frequency support mode of operation are also used in maximum power tacking mode of operation.

![Diagram of VSWT control system in maximum power tracking mode of operation.](image)

**Fig. 7** VSWT control system in maximum power tracking mode of operation.

3 Simulation Results

A library with the models of the power system components (WTs, control systems, etc.) has been developed using Simulink and Matlab code. The models described in Section 2 are combined in order to obtain the model of a VSWT connected to a power system. For the purposes of this study it is assumed that the wind plants are modeled as an equivalent VSWT. Furthermore, it is assumed that the system load remains constant during simulation time interval and the only source of demand variability is the power produced by the wind plants. This is modeled considering wind power as negative power demand in (8). The nominal installed power of the wind plants is assumed 25% and 40% of the respective nominal installed power of the conventional units. It should be noticed that only primary frequency control has been assumed for the derivation of the results presented next.

A random wind speed time series is the input to the model. Wind speed time series average is 9.2 m/sec and its duration is 180 sec. For the reproduction of the wind speed time series a Fourier synthesis method is applied which employs the Von Karman spectral density function of the wind turbulence [6].

The wind speed time-series used in both scenarios is shown in Fig 8. The wind power injected to the grid for frequency support and maximum power tracking modes of operation for both examined scenarios are shown in Figs 9, 11 while system frequency is shown in Figs 10, 12.

In frequency support mode of operation the control system of VSWTs continuously adjusts output active power in order to alleviate frequency deviations as shown in Figs. 10 and 12.

![Graphs showing wind speed and power production.](image)

**Fig. 8** Wind speed (m/sec)

**Fig. 9** Power produced by the wind plants for 25% wind penetration.
The side effect of the frequency support facility is the reduction of the wind power production, as this is depicted in Figs 9, 11. The results are quantified and summarized in Table 1 where it is obvious that frequency deviation but also mean wind power production are reduced in frequency support mode of operation.

Table 1 Simulation results

<table>
<thead>
<tr>
<th>Wind Penetration</th>
<th>25%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Wind Power (p.u.)</td>
<td>FS</td>
<td>MPT</td>
</tr>
<tr>
<td>0.1212</td>
<td>0.1373</td>
<td>0.1869</td>
</tr>
<tr>
<td>Frequency Std (Hz)</td>
<td>0.0368</td>
<td>0.0414</td>
</tr>
</tbody>
</table>

Where,
FS: Frequency Support
MPT: Maximum Power Tracking

4 Conclusion

As penetration of wind power becomes significant major technical issues such as frequency support emerge. In this paper, the capability of VSWTs to support the frequency of the system is investigated. A control strategy depending only on local frequency measurements without the need of central control is simulated. The proposed control system presents several advantages such as, low cost, easy expansion, increased redundancy and simplified supervisory control. Furthermore, instead of measuring wind speed this can be reliably and accurately estimated. In this way reliable estimations of the available wind power are produced in real time. Taking into consideration the accurate and fast response of power electronics there are no significant errors introduced.

Simulation results are provided proving the validity and the effectiveness of the proposed method.

References: