ENABLING FREQUENCY AND VOLTAGE REGULATION IN MICROGRIDS USING WIND POWER PLANTS

ABSTRACT
With higher penetration of renewable energy sources like wind energy, its utilization for the provision of ancillary services in the form of frequency and voltage regulation is imminent. This paper deals with the capability of wind energy to provide these services in a microgrid environment with the consideration of different generation mixes of wind and conventional energy. A novel hysteresis control algorithm is implemented in the wind control system to compensate for the shortcomings of droop control during certain wind conditions. The microgrid model is simulated in Matlab/Simulink environment to compare the system frequencies and voltages with and without the control strategy.

1. INTRODUCTION
Wind power is an asset to reduce dependence on fossil fuels, but the major problem with higher wind penetration in a microgrid environment is its intermittent nature which affects the power quality of the electrical grid. A microgrid usually consists of various distributed sources like wind, solar, diesel, micro-hydro generators etc. In this paper, only wind and conventional synchronous generators are the sources considered in the microgrid. During an islanded operation, the main purpose of the wind turbine along with the conventional generators is to meet the load requirements. Conventionally, the variable-speed wind power plants (WPP) are made to operate at the maximum possible generation for a given wind speed. Out of the different types of wind turbines, the most widely used is the Double Fed Induction Generator (DFIG) type [1]. The major advantage of using a DFIG type wind turbine is its flexibility in maintaining the desired frequency and voltage by controlling the power electronic interfaces.

2. MICROGRID CONTROL OBJECTIVE
The objective of the paper is to develop a microgrid model with adequate generation mix of wind and conventional generators. Frequency control deals with the balance between the active power generation and load. So in order to maintain the frequency within its proper limits, the control algorithm to maintain the power balance must be fast enough. Wind turbines are considered to act like negative loads and are not quite extensively considered as a power plant. They were never conventionally used to participate in frequency control as it was difficult to control their power generation. But whenever there is sufficient wind available the reference setting could be changed to a sub-optimal operating point so as to have an indirect reserve power for frequency regulation [2]. The wind power plant along with the synchronous generators must also actively participate in voltage control by maintaining reactive power balance. The constantly evolving IEEE 1547 standards [3] are utilized to govern the interconnection and operation of distributed generation.

2.1. Frequency Control
Due to a power imbalance caused within a microgrid system, the different Distributed Generators (DGs) try to release or absorb kinetic energy in order to maintain the frequency within limits, which in turn is responsible to sustain the stability and security of the power system. While inertia response is necessary for system stability and security, it must be accompanied by frequency response in order to limit the frequency excursions. In a standard microgrid testbed such as CERTS [4] it is suggested to limit the frequency within ±1.2 Hz deviations from the nominal value.

2.1.1 Droop Control
In case of a conventional DG the speed is dictated by a governor system which controls the opening of the gates/nozzles in turn to control the frequency. Owing to higher or lower steam production/water flow, the conventional synchronous generators vary their output, hence responding to deviations in the frequency. Therefore, the gate position is controlled by a droop curve in order to limit the frequency fluctuations and eventually maintain the frequency at its desired set point [5]. The droop for a governor system is given by the relation:

\[
\text{Droop} = \frac{\% \text{ Speed reference change}}{\% \text{ Gate position change}} \times 100
\]

For a conventional generator the droop varies typically between 1-5 %.

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manner by producing less than the available power hence providing an indirect reserve [6].

Variability and unpredictability in wind power generation has generally kept wind power plants from participating in voltage and frequency regulation. In a typical operating mode, wind power plants are made to operate at the maximum possible generation for a given wind speed. Figure 1 shows the general mechanical power characteristic curves of wind turbines with varying wind speeds. The tracking characteristic is defined by four points: A, B, C and D. The wind turbines are assumed to have coinciding C and D points. Between points A and B, the tracking characteristic is a straight line. Between points B and C/D, the tracking characteristic is the locus of the maximum power of the turbine at various wind speeds. Beyond point D, the reference power is a constant equal to one per unit i.e. beyond the rated wind speed (10 m/s in this example), the pitch angle controller action is activated to adjust the aerodynamic torque to a constant rated value. It is also apparent that if required, the output of the wind turbine can be changed by varying the rotor speed for a given wind speed. The output of the rotor/generator side converter is manipulated to control the output power of the wind power plant. Therefore, to control the DFIG output, a control scheme may be applied to vary the rotor direct-axis component, \( I_d \) and quadrature axis, \( I_q \) values to achieve the required power output set point.

The usage of renewable energy sources with conventional energy sources may become feasible in a microgrid environment if the renewable energy sources were used for frequency and voltage regulation. With the increase of wind power plants in the power systems, avoiding them from voltage and frequency regulation services could lead to greater frequency excursions or even blackouts.

2.1.2 Hysteresis Control for Wind Generation

As the wind is intermittent in nature, using droop control continuously for a wind turbine is not an efficient method. The Weibull distribution [7] gives a description of the variability of wind speed at a particular location. At any location, there comes a period when the wind speed dips to levels where sufficient power from the wind turbine cannot be extracted. During this period, the conventional generators pick up the load imbalance and help in regulating the frequency. If the wind generator follows the droop control signal during the speed dip period, the set point for the active power reference reaches a very low value and owing to the low frequency deviations (as the synchronous generators were regulating the frequency) it would continue following the droop from the low set point even when the wind generators have a higher generation capability. This would cause an unnecessary loss of wind power and an increase in power from the synchronous generator. Instead, there is a modification made to the wind control system where the droop control is deactivated when the wind power goes below a fixed low point and keeps operating at the maximum power reference point available at the low wind until the output reaches the fixed high point. The control is then returned back to droop control for normal load following operations. The hysteresis high point in this case is considered to be 75% of the rated power while the hysteresis low point is 50%. The flow chart for the Hysteresis control is shown in Fig. 2.

![Hysteresis Control Flowchart](image)

Fig. 2. Flowchart for Hysteresis control of WPP.

2.2. VOLTAGE REGULATION

Voltage regulation is important in a power system to improve its stability and reliability. Voltage regulation and reactive power regulation go hand in hand.
2.2.1 Excitation System

The excitation system used for the conventional generator is a type DC1A-DC commutator excitation system model [8]. The excitation system senses the terminal voltage and compares it with a reference value hence producing an error signal. The error signal is amplified by a regulator which produces an output signal to control the exciter. The excitation of the field then aids in maintaining the terminal voltage at its nominal value.

2.2.2 Voltage Control in Wind Generation

The wind generator can operate either in voltage control mode or var control mode. In voltage control mode, the reactive power is adjusted in order to maintain nominal voltage at the terminals, while in var control mode; the reactive power generated or absorbed is maintained at a constant value by setting the reactive power reference. As the load always contains some reactive component, the DFIG is able to actively participate in voltage regulation by adjusting its reactive power generation/absorption. The DFIG follows a voltage droop characteristic as shown in the Fig. 3. The current is the reference value injected into the rotor through the rotor side converter. If the current becomes negative, it absorbs reactive power while reducing the voltage and when the current becomes positive, it generates reactive power in order to increase the voltage across the terminals. The V-I wind turbine characteristics is shown in Fig. 3.

![Wind turbine V-I characteristics](image)

Fig. 3. Wind turbine V-I characteristics.

3. MICROGRID DESCRIPTION

In the microgrid model test system shown in Fig. 4, there are two wind generators and three synchronous generators considered with a mix of different megawatt ratings. The microgrid model was tested with data from two separate locations, Floydada, TX and Fortuna, CA [9,10] for different generation mixes like 50%-50%, 60%-40%, 70%-30%, 80%-20% and 90%-10%. A 60%-40% generation mix would mean that 60% of the total rated power is from the conventional synchronous generators while the rest 40% belongs to the wind generation. The generation mix for the microgrid added up to a total capacity of 15 MW. All generators are assigned a 1% droop which ensure the full operation of governors for a frequency deviation of ±0.6 Hz and equal participation from all generators. The load data for a typical day at the locations were extracted from the ERCOT website [11]. These generation mixes were simulated for different loading conditions during a typical day for each month of the year. Bus 1 of the test system is considered to be the point of common coupling between the microgrid and the main grid, to support the grid connected mode. Branches 1-2, 1-3 and 1-4 represent the distribution lines. There are three lumped loads at different locations which are fed mainly by the DGs.

4. PERFORMANCE INDICATORS

As the main idea of applying the proposed control strategy is to compare its performance with an existing strategy, there are a few performance indicators that help quantify the indicators. For frequencies, the two criteria to consider are: (A) the frequency should be within the range of ±2% for 95% of the time and (B) the frequency should never cross the limit of ±15% at any time during the microgrid operation [12]. In case of bus voltages the two criteria to be met are: (C) the 1 second RMS value voltage should be between 90% to 110% of the nominal value and (D) the 1 cycle RMS value voltage should be between 70% -115% of the nominal value.

5. RESULTS

As previously mentioned, various generation mixes were considered. The performance criteria failed for a few cases, but there were many cases when the use of the controller performed well when compared with the no controller case. For example, the controller’s performance was tested for the 60%-40% mix subjected to a 24 hour load profile, and was compared with the
condition where the DFIG was operated at its maximum power for the particular wind speed, i.e., without the controller. At around 1 PM (hour 13), the wind speed drops and hence the wind power output is also reduced. The controller allows the wind power plant to follow the maximum power point until an adequate amount of wind speed is available. At 2 PM (hour 14), an adequate amount of wind speed is available; hence the controller starts driving the power output according to the requirements. The wind power plant without the controller always operates at the maximum power point. Due to this type of operation, spikes in frequency may be observed in Fig. 5. It can be observed that the microgrid controller satisfies criteria A and B while they fail for the case when the controller is not applied.

![Fig. 5. Frequency variations for cases with and without the control scheme.](image)

Figure 6 shows the voltage variations within the microgrid. It can be observed from the figure that the voltages remain closer to the nominal value with lower deviations when the controller is applied, while in the no control case, there is more distortion. Both the control and no control cases satisfy criteria C and D.

![Fig. 6. Voltage variations for with and without the control scheme.](image)

The active and reactive power generated at the synchronous generator and wind turbine buses for both with and without control are shown in Figs. 7 and 8 respectively, where it can be observed that the wind turbine loses around 12% of the total available power for the 24 hour period when the controller is applied instead of using the no control option.

![Fig. 7. Power at the wind generator bus.](image)

Fig. 7. Power at the wind generator bus.

![Fig. 8. Power at the synchronous generator bus.](image)

Fig. 8. Power at the synchronous generator bus.

As previously mentioned, in order for wind energy to participate in frequency regulation, particularly for up-regulation, it must operate at a lower point as compared to its maximum capability so as to create an indirect reserve for immediate usage. For this study, the data specifying the amount of wind power spilled due to regulation is studied and the variation of this loss with increasing wind speed is shown in Fig. 7. Floydada, TX faces a wind power spillage of around 12% in order to provide regulation when the wind penetration is 40% of the rated capacity. This is due to high availability of wind in this region which is good for producing power, but at the same time increases the spillage. The generation mixture was also simulated at Fortuna, CA. It loses only 8% of wind power in order to provide regulation at 40% penetration. This is due to highly intermittent nature of wind in this region. Fig. 9
shows the graph for wind power losses as compared to the wind power penetration for Floydada, TX and Fortuna, CA locations.

![Graph showing wind power loss comparison for Texas and California](image)

Fig. 9. Wind power spillage due to regulation.

Simulations were carried out for the locations with different generation mixes. Table 1 gives a summary of ideal generation mixes for the two locations for each month. These mixes are best suited for that particular month as they satisfy all the performance criteria that were mentioned in Section 4. It can be observed that for some cases, higher wind penetration is better when the controller is applied as compared to cases when the controller is not applied.

Table 1. Ideal generation-mix for each month

<table>
<thead>
<tr>
<th>Month</th>
<th>Ideal Generation-Mix</th>
<th>Floydada, TX</th>
<th>Fortuna, CA</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>NC</td>
<td>WC</td>
</tr>
<tr>
<td>January</td>
<td>70-30</td>
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<tr>
<td>December</td>
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</tbody>
</table>

* NC: No Controller, WC: With Controller

6. CONCLUSIONS

A novel control scheme for frequency control in wind power plants connected in a microgrid environment is proposed. This control scheme enables wind power plants to participate in frequency regulation, utilizing its untapped potential/capability to provide variable active power assuming there is adequate amount of wind speed available. This control bridges the gap for using droop control for wind power plants in the same manner as that available for synchronous generators. To test this control methodology for implementation in the real world, a test system was modeled in Matlab/Simulink. The three loads connected to this system were modeled to accommodate hourly load changes for a day. To accommodate the resolution of hourly load data, the system was setup to use hourly wind data for the wind turbines.

The simulation study was done for numerous scenarios which included variation of the generation mix configuration from 10% to 50% wind power to identify the effects of high penetration of wind power in a microgrid. These scenarios also included testing of the microgrid with and without the proposed control strategy for comparison. Observations made from this study revealed the effectiveness of the control methodology to smooth out the frequency and voltage fluctuations appearing in the microgrid islanded system. A reliable generation mix configuration of conventional and wind power generation for the two cities was also deduced and was found to be related to the overall wind capacity in that location throughout the year.

7. Future Work

This control methodology and the system can be easily modified and scaled to specific requirements and can be used to study integration effects of other renewable or non-conventional energy sources. The next step can be the development of a methodology for assessing and controlling a microgrid equipped with different kinds of non-conventional energy sources like solar photovoltaic plants, fuel cells, internal combustion engine generators, micro-turbines, battery energy storage systems, and plug-in hybrid electric vehicles. These non-conventional energy sources have the potential to support a microgrid with frequency and voltage regulation. Inclusion of these energy sources into the microgrid would help to strengthen its reliability. The microgrid can be made smarter by using faster controller and perhaps intelligent technologies.

8. ACKNOWLEDGMENTS

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9. APPENDIX

A. Synchronous Generator:

MVA Capacity: 4.5 / 4 / 3.5 / 3 / 2.5 MVA
Line to Line Voltage: 4160 V
Frequency: 60 Hz

\[ x_d: 1.305 \text{ pu} \]
\[ x_q: 0.296 \text{ pu} \]
\[ x_t: 0.252 \text{ pu} \]
\[ x_s: 0.474 \text{ pu} \]
\[ x_d' : 0.243 \text{ pu} \]
\[ x_t' : 0.18 \text{ pu} \]
\[ T_d: 1.01 \text{ sec} \]
\[ T_q: 0.053 \text{ sec} \]
\[ T_{mp}: 0.1 \text{ sec} \]

Stator Resistance (Rs): 0.0028544 pu
Inertia Coefficient: 5 sec
Friction Factor: 0
Pole pairs: 2

B. Double-fed Induction Generator:
MVA Capacity: 4.5 / 4 / 3.5 / 3 / 2.5 MVA
Line to Line Voltage: 4160 V
Frequency: 60 Hz
\( R_s: 0.00706 \) pu
\( L_{ls}: 0.171 \) pu
\( R_r': 0.005 \) pu
\( L_{lr}': 0.156 \) pu
\( L_m: 2.9 \) pu
\( H(s): 5.04 \)
Friction Factor: 0.01
Poles: 3
\( X_s: 0.04 \)

C. Line Impedances
1 – 2: 0.4612 + j1.652
1 – 3: 0.4612 + j1.652
1 – 4: 0.4612 + j1.652
2 – 5: 0.1153 + j0.413
2 – 6: 0.2306 + j0.826
2 – 7: 0.1153 + j0.413
3 – 8: 0.2306 + j0.826
3 – 9: 0.2306 + j0.826
4 – 10: 0.1153 + j0.413
4 – 10: 0.2306 + j0.826
4 – 10: 0.1153 + j0.413

10. REFERENCES