MICROGRID COMPATIBILITY OF PHOTOVOLTAIC AND WIND POWER SYSTEMS

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ABSTRACT

Renewable energy sources, like wind and photovoltaic (PV) power plants can be used to provide grid-friendly services in the form of additional active and reactive control for frequency and voltage regulation respectively. Current wind and PV power systems are operated in simply an energy supply mode and are not required to participate in ancillary power services. These services will become critical when operating in an islanded micro-grid. The maximum active and reactive power capability of the wind and photovoltaic power plants along with their limitations are formulated and discussed. A direct power control scheme is simulated with both types of resources in a test microgrid. Simulation results display the potential of wind energy when utilized either in parallel with or islanded from the main grid.

1. INTRODUCTION

The need for high service availability, high environmental quality and high power quality has dramatically increased the desirability of renewable energy resources in the power grid. The advantage of the renewable class of distributed generation is that their fuel source (water, sunlight or wind) is abundantly available, and, because of their modular nature, they can be easily deployed near customer sites, thereby decreasing the over-dependence on typical radial distribution lines to bring power from central generating locations.

However, the application of renewable as well as other DERs, especially in a microgrid environment is fraught with technological challenges [1]. They are significantly different from the conventional forms of generation in that solar insolation and wind are intermittent in nature, and therefore, at any given point in time, a desired or commanded amount of electric power output from these renewable resources cannot be guaranteed. As such, when applied in a microgrid environment, the customer’s kW capacity demand may not be met at all times leading to frequency excursions that may become uncontrollably low, eventually leading to a blackout. Another serious disadvantage of present-day inverter-fed renewable energy plants is that the inverter is forced to operate at unity power factor, which means that these plants cannot supply reactive power to the microgrid. This form of operation may lead to low voltages during peak load conditions, and could, in fact, lead to a voltage collapse because of the lack of dynamic reactive reserves.

The renewable energy resources are incapable of responding to frequency and voltage changes on the distribution system. For example, the present preferred method of operation of a PVP is to track the maximum power point at unity power factor [2-3]. At high penetrations, this type of control can be detrimental to overall system operations. In order to have greater control over distributed resources in a microgrid, a communication-enhanced inverter-based control scheme will be developed for both active (P) and reactive (Q) power control. Active and reactive power modulation are only now beginning to be discussed in the literature [4-6]. Such inverter-based controls will become critical as the penetration of renewable resources continues to grow.

Some solutions for correcting these two serious drawbacks of renewable energy plants – namely the inability to respond to the dynamic nature of the microgrid’s frequency as well as the inability to regulate microgrid voltage are presented in this paper.

2. MICROGRIDS

Microgrids are autonomous small-scale power grids at the lower distribution voltage levels consisting of interconnected loads and DER [7-9]. As an integrated system, a microgrid is capable of operating in parallel with the grid or in an islanded mode, thus providing higher reliability and flexibility of operation. Although some features of the microgrid exist in the present state-of-the-art, the overall concept of the microgrid is still far from being widely adopted. Nevertheless, it is serving as a catalyst for the development and deployment of many DERs [10-15]. To provide uniformity, the interconnection and operation of distributed generation, including PV and wind plants on the grid is governed by IEEE 1547 standards [12-13].

A microgrid can provide immunity from system-wide disturbances as long as certain operating conditions are satisfied. In the past, there has been a general reluctance to using renewable energy-based generation in an energy-limited grid, such as a microgrid. Most devices within RENDER, such as solar photovoltaic plants, or wind power plants, or fuel cell
plants, have to be connected to the grid through inverters; since inverter-fed energy sources lack adequate short circuit capacity, they cannot supply fault currents during system disturbances. Consequently, these devices are forced to trip at the first sign of a system problem, unless low- or high-voltage ride through capabilities are provided for these inverter. More and more inverters are now appearing in the market equipped with this capability [4-5, 16-17].

Some of the more complex technical challenges facing the operation of a microgrid in the presence of renewable resources may be summarized as follows:

- Surviving fault-induced transients.
- Providing adequate dynamic damping to ensure oscillatory stability.
- Providing adequate voltage and frequency regulation.
- Ensuring transient/voltage stability of the microgrid.
- Providing communication among entities within the microgrid.
- Assessing the dynamic state of the microgrid in real time.

3. WIND POWER PLANT (WPP)

There are two major classifications amongst wind generation units: fixed speed generation and variable speed generation. The fixed speed generators have a design speed for which they have maximum efficiency whereas for other speeds their efficiency is lower. Variable speed generators have the maximum power tracking capability that extracts maximum available power out of the wind at different speeds thereby resulting in more efficient operation. Also the variable speed generators reduce mechanical stresses on the turbine thus increasing the lifetime of the turbine. Thus variable speed generators are more commonly installed.

When designing a wind turbine the amount of power generated by the turbine can be associated with the torque generated by the wind. The relationship between the torque and the wind can be formulated as below.

\[
T_{\text{wind}} = \frac{1}{2} \rho A V^3 \frac{C_p}{\omega_r}
\]

Where,
- \( \rho \) is the density of air.
- \( A \) is the rotor area.
- \( V \) is the wind velocity.
- \( \omega_r \) is the rotor speed.

And,
\[
C_p = c_1 \left( \frac{C_2}{\lambda_i} - c_3 \beta - c_4 \right) \frac{\lambda^2}{\lambda + 0.08 \cdot \beta} + c_6 \lambda
\]

\[
\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \cdot \beta - \frac{0.035}{\beta^3 + 1}}
\]

\( \lambda \) is the tip speed ratio (TSR)
\( \beta \) is the pitch angle of the wind turbine.
c1-c6 constants are provided by the manufacturer.
Also, \( C_p \) is called the power transmission coefficient.

The different variations of power level can be seen in Fig. 1 with varying pitch angle and rotor speed.

![Fig.1. Variation of power with respect to the pitch angle and wind turbine speed. (wind speeds 10m/s and 12 m/s).](image)

Amongst the variable speed generators, there are two major kinds, synchronous generators with direct power electronic converters and doubly fed induction generators with rotor side power electronic converters. Both have the above mentioned advantages of variable speed generators but the power electronic ratings of the two machines are different. A doubly fed induction generator (DFIG), as shown in Fig. 2, allows us to use converters of partial rating instead of conventionally used full scale converters. The power electronics used in this topology are rated around 30-40% of the total rating of the system. Usually, the slip varies between 40% at sub-synchronous speed and -30% at super-synchronous speed.

2.1. P-Q Capability

The capability of a DFIG presents similarities to the conventional synchronous generator capability. Reactive power capability depends on three factors, active-power generated, the slip and the limitations due to stator and rotor maximum-currents as well as the maximum rotor voltage. In order to understand the power capability curve, the following circuitual relationships are obtained from the equivalent circuit of DFIG as discussed in [18]. The active power varies with the wind speed and the slip is assumed to be constant here. Other three limitations can be formulated as discussed below.
(a) **Stator current limitation**

This limit takes into account the stator heating due to the stator winding’s Joule losses. The PQ curve depicting stator current limitation is straightforward. The curve will form a circle with a center at 0 and a radius of the product of the stator current and the stator voltage as described in equations below:

\[
\text{Center} = 0
\]

\[
\text{Radius} = |I_s| \cdot |V_s|
\]

(b) **Rotor current limitation**

This limit takes into account the rotor heating due to the rotor winding’s Joule losses. The rotor current limitation in PQ diagram of a DFIG is derived by assuming a rotor current with the rated magnitude and a variable angle relative to the stator voltage. The formulated power equation with a given rotor current and a given stator voltage is free of slip. The angle is varied with a fixed rotor current magnitude which forms a circle in the complex plane with the following center and radius equation.

\[
\text{Center} = -|V_r| \cdot \left[ \frac{1}{Z_s + Z_m} \right]
\]

\[
\text{Radius} = |I_r| \cdot |V_s| \cdot \left[ \frac{Z_m}{Z_m + Z_s} \right]
\]

(c) **Rotor voltage limitation.**

The rotor voltage limitation is essential for the rotor speed interval, because the required rotor voltage to provide a certain field is directly proportional to the slip. Thus, the possible rotor speed is limited by the possible rotor voltage.

\[
\text{Center} = -|V_r| \cdot \left[ \frac{Z_r + Z_m}{(Z_r + Z_s) \cdot Z_m + Z_s \cdot Z_r} \right]
\]

\[
\text{Radius} = \frac{|V_r|}{s} \cdot |V_s| \cdot \left[ \frac{Z_m}{(Z_r + Z_s) \cdot Z_m + Z_s \cdot Z_r} \right]
\]

Fig. 3 displays the effects of these limitations on the PQ capability of the system. The blue line in the figure constitutes the stator current limitations on the DFIG. The red line displays the rotor current limitations and the green lines represent the limitations due to rotor voltage. Because of these limitations DFIG can operate only in the overlapping region of all the three limitations. This region lies between red upper curve and blue lower curve.

Fig. 4 displays the variation of capability according to the wind speed. In this figure, the DFIG machine operating region after taking care of the three limitations is displayed for wind speeds ranging from 9 m/s to 14 m/s. As observed, the DFIG capability of providing active and reactive power decreases with decrease in the wind speed. Also, DFIG machine operating region max out at 12 m/s and the pitch angle of the wind turbine is to be controlled above this wind speed to avoid any damage to the system.
3. PHOTOVOLTAIC (PV) POWER PLANTS (PVP)

Photovoltaic (PV) power plants are only capable of providing active power because of its' DC type system build. So, PV systems generally rely on inverters to provide reactive power support.

Inverters can be used to define the phase angle of the current going to the mains grid, hence can be regulated as required. One fundamental limitation of inverters is the maximum current carrying capacity. If an inverter is to be designed for providing additional reactive power support, it needs to be oversized to accommodate the increased amount of current in the system. Because of the introduction of reactive power, we then consider apparent power with zero power factor as the input (instead of active power) to fulfill the law of conservation of energy and a combination of active and reactive power at the output [24]. Also, PV faces one more limitation due to intermittent availability of raw power and the use of an efficient controller.

Within these limitations, the PV-inverter integrated system can be controlled with a response time in the order of milliseconds. Figure 5 shows the capability of a PV system and general efficiency of different inverters [26]. This figure displays the operating region of a PV-inverter integrated (PV) system. PV system can operate efficiently in the yellow region with very low response time. When the input power to the inverter drops below 5%-15% of the rated power (Figure 5, part b), the inverter shuts down because of unavailability of sufficient power to drive itself. Also, according to the manufacturer’s ratings, the inverter can be overloaded for a short period of time.

4. SIMULATION

4.1. Circuit Description

A 1.5 MW wind turbine connected to a 13.2 kV, 6-bus test distribution system exports power to the grid through a 2 km, 13.2 kV feeder line, as shown in Fig. 6.

Wind turbines using a DFIG, consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter modeled by voltage sources. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. In this type of model, the IGBT voltage-sourced converters (VSC) are represented by equivalent voltage sources generating the AC voltage averaged over one cycle of the switching frequency. This model does not represent harmonics, but the dynamics resulting from control system and power system interaction is preserved.

Figure 6. Simulation model of Microgrid.

4.2. Direct Power Control

By controlling the state variables like rotor current, rotor speed to achieve active and reactive power control, direct power control scheme is implemented in this system. The simulation results display that the wind power system under observation, follows the commanded active/reactive power, as shown in Fig. 7. This simulation shows the time taken by the WPP to respond. First sub plot is displaying the commanded active power in p.u. from the WPP, whereas the second subplot shows commanded reactive power in p.u. Third and fourth subplot shows the active and reactive power response respectively according to the commanded value.
4.3. Wind power system in Microgrid dynamics

The wind power plant is now connected to the microgrid network to simulate it under load. This system is tested first with the wind power plant connected as a source, not participating in frequency or voltage regulation. The system is tested for three-phase fault conditions near bus 6 and bus 3. The voltage – frequency responses on each bus can be seen in Figure 8. We see that, if a fault is away from the slack bus (Bus 1), system attains stability after some time. But if the fault is near the slack bus, the system becomes unstable. This unstable operation can be avoided if the WPP is allowed to participate in frequency regulation by varying its’ active/reactive power according to the changes in frequency and voltage profile.

5. FUTURE WORK AND CONCLUSIONS

Capability and limitations of wind and photovoltaic power plants were discussed and a microgrid model was simulated to satisfy the claims.

In the next piece of work, a controller for the wind power plant would be designed which would autonomously control the active and reactive power output coming from the WPP according to the frequency of the system and the voltage profile of the bus connecting the WPP to the grid. This would show that a WPP, supporting a microgrid increases the stability. Also, a DPC enabled photovoltaic (PV) source would be incorporated in the system to observe the combined dynamics.

6. ACKNOWLEDGMENTS

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7. APPENDIX

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$V_s$</td>
<td>DFIG Stator Voltage.</td>
</tr>
<tr>
<td>$I_s$</td>
<td>DFIG Stator Current.</td>
</tr>
<tr>
<td>$V_r$</td>
<td>DFIG Rotor Voltage.</td>
</tr>
<tr>
<td>$I_r$</td>
<td>DFIG Rotor Current.</td>
</tr>
<tr>
<td>$Z_m$</td>
<td>Mutual Impedance between stator and rotor.</td>
</tr>
<tr>
<td>$Z_r$</td>
<td>Rotor Impedance.</td>
</tr>
<tr>
<td>$Z_s$</td>
<td>Stator Impedance.</td>
</tr>
</tbody>
</table>

Fig.8 Fault on the microgrid with a clearing time of 0.27 Sec
8. REFERENCES


