Use of Energy Storage to Mitigate Frequency Variations in a Load Frequency Control Model

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The increase of renewable and intermittent energy sources replacing more stable and conventional sources such as gas-fired or coal plants in the power grid could lead to large frequency variations, sometimes exceeding that of grid limits (±1% of 60Hz). The use of specific storage devices (with individual time constants and duration of storage) reduces excessive frequency variations due to renewable energy. Various observations in relation to the time constants and ramp rates are also noted, mainly the instabilities due to conflicting time constants.

Keywords: energy storage, frequency variations, load frequency control model

INTRODUCTION

Although there are currently no federal mandated laws requiring the use of renewable sourced energy in the United States, the individual states have implemented renewable portfolio standards (RPS) that sets renewable penetration goals.

The Colorado Public Utilities Commission has set the goal of having 30% of the retail electricity sales in Colorado by the year 2020 to be from renewable energy sources [1]. This increased in penetration of intermittent and variable renewable energy sources could lead to large frequency variations, in some cases exceeding grid limits of ±1% of 60 Hz. At smaller penetration levels, the variations do not have as large of an impact compared to higher levels (Fig.1)

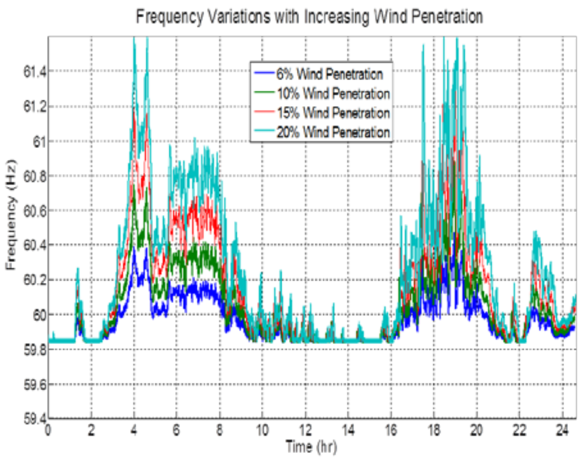

Fig. 1. Frequency Variations with Increasing Wind Penetration

Limits on the grid frequency, ±1% of 60 Hz (corresponding to 59.4 Hz and 60.6 Hz) are enforced to ensure proper operation of induction generators (in the case for the lower limit of 59.4 Hz) and also to limit losses in power system components like transformers (in the case of upper limit of 60.6 Hz).

METHODOLOGY

Assumptions and Model

A load frequency control model with four different types of generation is used: a) gas-fired plant b) wind farm c) short-term storage and d) long-term storage. This would serve a customer load with the long-term storage plant connected via a transmission line to the rest of the generation. This transmission line is assumed to have sufficient capability for power transfer.

The load is assumed to be a constant (MWh) for now. This is show that with the variations from the wind farm alone could lead to excessive frequency variations.

The wind turbines in the wind farm are assumed to be fixed-speed wind turbines. The wind turbines scattered over a geographical distance is assumed to see the same wind speed, i.e. there is no aggregation in the power output from the combined turbines in the farm. It is known that the variability of wind decreases with the aggregation of multiple wind turbines across a geographical distance [2].

The load-frequency control model used is based on simple model with only two sources seen in Fig.2. The load-frequency and reactive voltage stability parts are decoupled in this model [3,4].

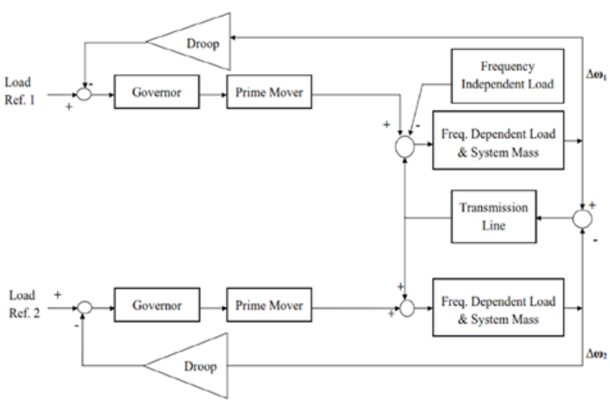

Fig. 2. Simple Load-Frequency Control Model

The system has the following parameters:

Table 1. Initial Storage Description

Type of Generation	Rated Power (MW)	Duration of Discharge at P_{rated} (MW)
Gas Fired Plant	300	Months
Wind Farm	250 (max)	Intermittent
Short-Term Storage	90	3-4 minutes
Long-Term Storage	120	3 hours to days

The short-term storage plant is initially assumed to be able to respond within a few 60 Hz cycles (designated as storage response time). The short-term storage plant although not designed to be of any particular architecture uses power output data gathered from a physical sodium sulfur battery in Minnesota operated by Xcel Energy [5].

However, the long-term storage plant, which is based on a pumped hydro system, has a response time of about 5-10 minutes. It should be noted that these values are initially assumed and observations later will show the effects of changing response times on the stability of grid frequency.

Simulation Scenarios

Simulation was run using wind speed data gathered from the National Wind Technology Center M2 Tower in Boulder, Colorado [6] on 10th September 2010. Wind speed data is then converted into power assuming a wind turbine efficiency of 50%. The total energy consumed by the load is 144 MWh over the course of 24 hours.

With about 10% penetration, the average energy delivered by the wind farm is about 15 MWh (Fig. 3). The rest of load is then supplied by the gas-fired plant and to a smaller extent, with a combination of the energy storage systems.

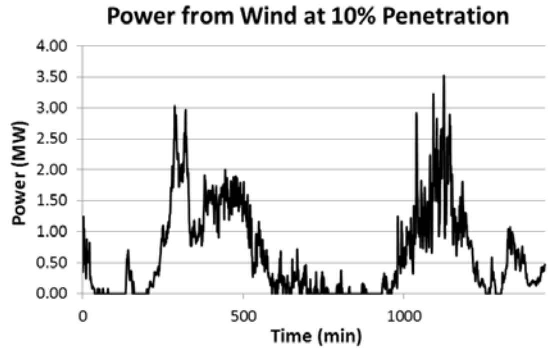

Fig. 3. Power from Wind at ~10% Penetration Level

Initial simulations used a rough control method for compensating drops in wind power. The short-term storage with its fast response time of several 60 Hz cycles is switched on when the wind is down and ramped up linearly. It is then discharging at rated power for 3-4 minutes and as it is reaches close to zero state-of-charge, the long term storage replaces the short-term storage system. Results and observations from this system have been published in a separate paper [7] and hence would not be discussed in detail here. However, conclusions from this scenario lead to a newer simulation scenario.

The second scenario now has the short-term storage using a PID controller in an active role to reduce frequency variations. The short-term storage now uses the sensed frequency deviations due to the variable wind power and charges (or discharge) accordingly to suppress frequency variations. This however violates the initial storage description of having duration of discharge of 3-4 minutes.

RESULTS

First Scenario

For a start, a baseline setting was obtained by running the simulation model without any energy storage systems with a wind penetration level of 10%. The following figure (Fig. 4) of the frequency variation without energy storage is shown below:

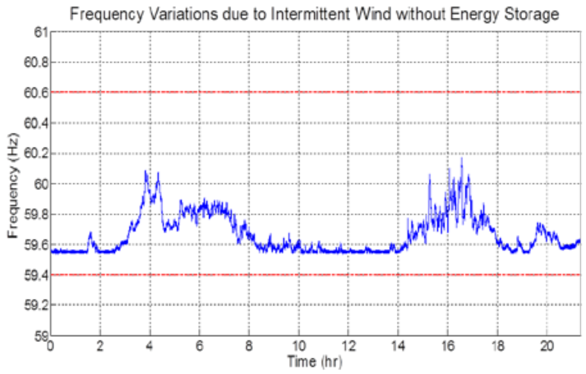

Fig. 4. Frequency Variations without Energy Storage

Next, an "unintelligent" method of utilizing energy storage to reduce frequency variation is implemented. This is done by discharging the energy storage when the wind power output is close to zero. This would correspond in Fig. 4, times between 0-2 and 8-14 hours. The following result is shown in Fig. 5.

First, the short-term energy storage system would discharge at its P_{rated} of 90 MW when there is no output power from the wind. When the system is close to its zero state-of-charge (SOC), i.e. at 3 minutes, the long term storage is switched on.

The response time for the long-term plant is about 10 minutes and is ramped up linearly until its P_{rated} of 120 MW. It is then cycled on and off as and when the wind farm does not have any power output.

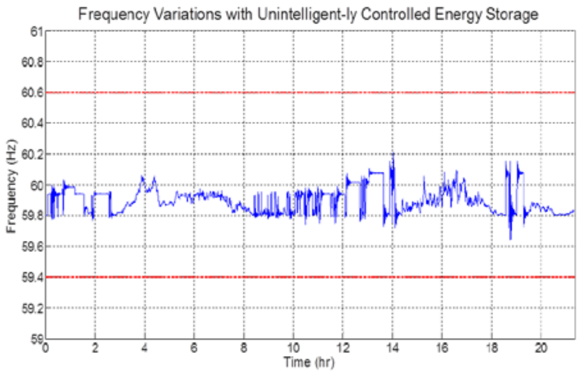

Fig. 5. Frequency Variations with Unintelligent-ly Controlled Energy Storage System

Fig. 5 shows that an unintelligently controlled energy storage system yields a worse frequency output when compared to a system without any energy storage system. The repeated switching in and out of various devices had increase the frequency spikes in the system.

Second Scenario

From this, it was realized that an energy storage system could be charged and discharged using a PID controller that senses the frequency deviation and compensates accordingly. Also, with its slower response time, the long-term storage plant could not compensate for the cycle range frequency changes. It is assumed that the short-term storage system have sufficient capacity (MWh) for regulating frequency. The model was run again with this controller and the following results are shown (Fig. 6):

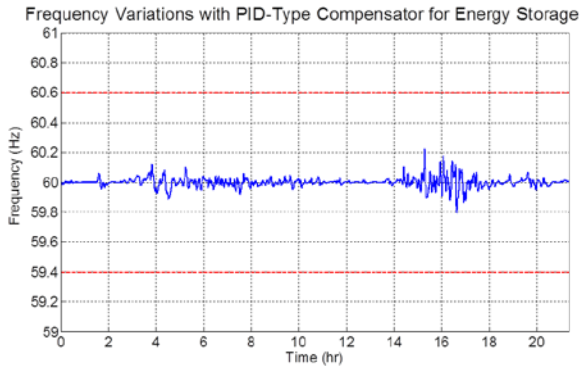

Fig. 6. Frequency Variations with PID-type Compensator for Energy Storage

It is clear that a PID-type compensator that regulates the frequency is effective. However, this system requires that the energy storage system have a high energy capacity (MWh) that is clearly impractical if an electrochemical type battery is assumed.

Observations

During simulation, several observations were found, such as:

a) Different response times of the various storage systems could either lead to an increase or decrease, of frequency variations with other time constants held constant (Fig. 7). It was observed that an energy storage system with a fast response time (≤ 1 second) created a larger oscillation as compared to a system with a slower (~5 seconds) response time. However, having a system that responds too slowly (≥10 seconds) would lead to increase in frequency oscillation.

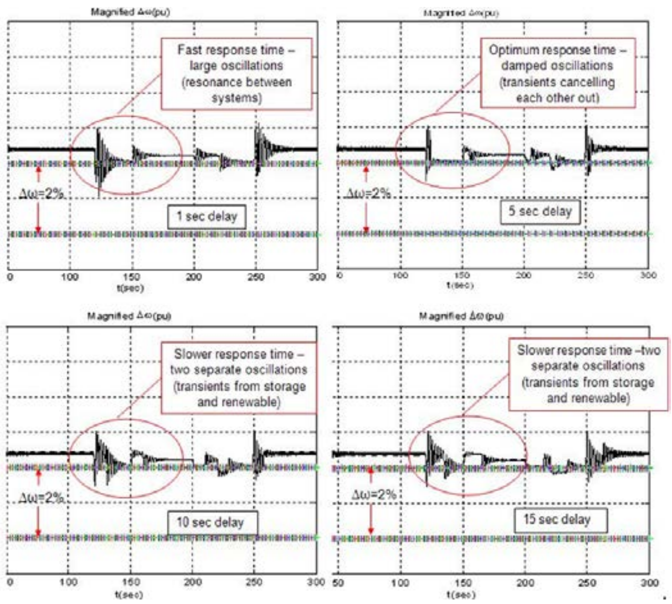

Fig. 7. Varying Response Times Leading to Changes in Frequency Variations

b) Without any energy storage devices, the frequency variations are almost proportionate to the size and power profile of the intermittent power penetration. This is shown in Fig. 1.
c) Differing time constants of the various interacting power sources (i.e. wind, gas-fired plant and energy storage systems) could lead to an unstable system. This is shown in Fig. 8. This also leads to the following point:
d) That the selection of proper speed-droop characteristics play an important role and at very small speed-droop values, un-damped oscillating frequency deviations would result (see Fig. 8)

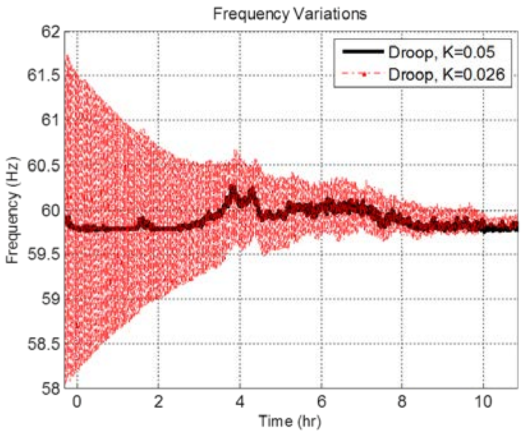

Fig. 8. Frequency Variations due to Differing Droop in the System

e) Peak-power tracking must not induce power oscillations due to a searching algorithm for finding maximum power point (for both wind and PV systems) [8]

CONCLUSIONS

It is shown here that energy storage systems do mitigate frequency variations due to intermittent renewable energy systems. However, the response times and internal characteristics of the various components in the system may cause the system to be an unstable one

FUTURE WORK

Future work includes more detailed modeling of the PID controller with a constraint on the capacity of the energy storage system. Non-ideal characteristics such as dead band in the time constants of the load-frequency model also have to be taken into account.

ACKNOWLEDGEMENTS

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BRIEF BIO

Michelle Lim received a B.S. degree in aerospace engineering and M.S. in electrical engineering from Wichita State University in 5/2006 and 8/2009, respectively. She has worked on the economic feasibility of integrating wind energy in the state of Kansas with a Department of Energy grant in 2009. Currently, she is an electrical engineering PhD candidate at the University of Colorado at Boulder.

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Frank Barnes received his B.S. from Princeton University in electrical engineering in 1954 and his M.S. Engineer and PhD from Stanford University in 1955, 1956, and 1958. He joined the University of Colorado in 1959 and appointed a Distinguished Professor in 1997. He was elected to the National Academy of Engineering in 2001 and received the Gordon Prize 2004 for innovations in Engineering Education from the National Academy. He is a fellow of IEEE, AAAS, and ICA and served as Vice President of IEEE for publication. In the last four years, he has been working on energy storage and the integration of wind and solar energy into the grid and the effects of electric and magnetic fields on biological systems