PUMP-STORAGE INTEGRATION WITH RENEWABLES – MEETING THE NEEDS USING VARIOUS CONCEPTS

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ABSTRACT

One of the primary tasks of Pumped Storage Power Plants (PSPP) in this era of rapidly growing renewable energy sources like wind and solar energy is to provide for energy storage while contributing to the stabilization of the electrical grid. Fast reaction to power unbalances and grid fluctuations may be achieved by using various configurations/types of pumped storage power plants, such as:

- *pump-turbines with fixed speed designed for fast reaction times*
- *pump-turbines with variable speed*
- *ternary units with hydraulic torque converter*

Each configuration has specific behaviours that offer different advantages and disadvantages. The current investigation illustrates the necessary considerations for determining what pumped storage characteristics are needed to support the grid with wind and other renewable, and how these characteristics vary according to the local region's installed mix and renewable energy generation situation and transmission constraints. Such considerations are necessary for correct decisions in the early planning stage for PSPP configurations.

INTRODUCTION

The power generated by Wind Turbine Generators (WTG) is cubically dependent on wind velocity, as shown in Equation 1 below, making wind power a very volatile source of electrical energy.

$$P_w = 0.5 C_p \rho A v^3 \tag{1}$$

P_w represents the wind power in Watts, C_p is the performance coefficient [-], ρ is the air density [kg/m^3], A is the rotor swept area [m^2], and v is the wind velocity [m/s]. Similarly, other forms of renewable energy sources, such as Photo-Voltaic (PV) power are volatile due to fluctuations in solar radiation and environmental temperature.

As wind and solar energy becomes more popular, the increase in installed capacity will inevitably impact the electrical grid behaviour in terms of grid state variables (voltage and frequency) deviations. In order to incorporate these energy forms into current grids and avoid power fluctuations and grid instability, additional energy storage capabilities are necessary that can provide high energy flows over long distances. In most developed countries, the so-called Grid Codes specify tolerable voltage and frequency deviations as well as other requirements such as Low Voltage Ride Through (LVRT) capability for Double Fed Induction Generators (DFIG) or minimum duration of Short Circuit Clearance that a Synchronous Generator (SG) has to stably withstand without being disconnected from the grid [1], [2].

The overall grid behaviour depends on local conditions, including the total installed generating capacity, the distance between individual consumers and power plants, the grid type, the density and rating of the transmission lines and the types of power plants installed. Previous investigations have demonstrated the local behaviour of SG (fixed speed) and DFIG (variable speed) pumped storage plants [3], [4]. This paper focuses on the grid behaviour showing the impact of various solutions (DFIG vs. SG).

It also has to be considered that a wind farm output may be smoothed through coordinated control in order to reduce sudden power oscillations, as shown in Figure 1 [5].

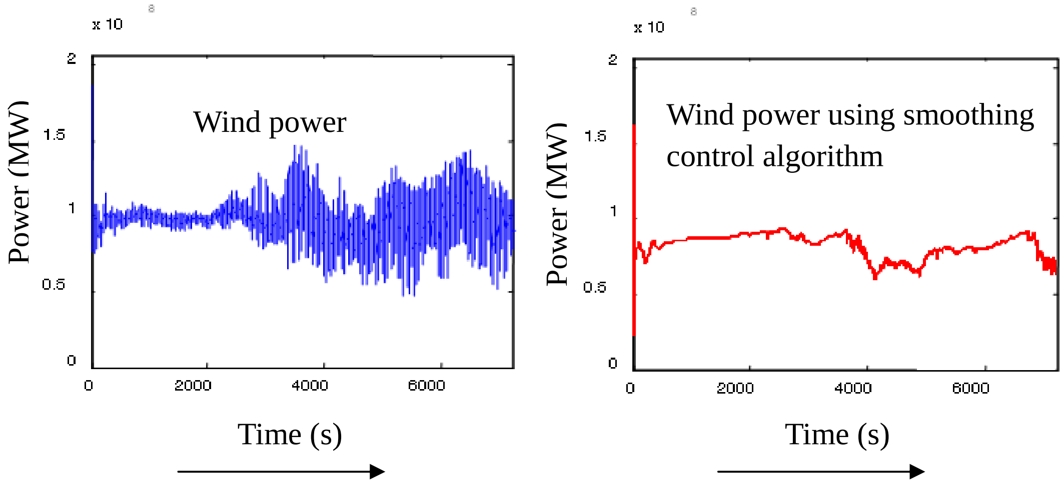


Figure 1: Influence of smoothing control algorithm on wind farm power output [5].

The installation of HVDC grids seems to offer both technical and economic advantages in regard to the connection of wind farms to the grid as well as energy flow over long distances [6]. The main advantages would be lower transmission losses, no reactive power supply necessary, no need for synchronization of grid subsystems as well as higher grid stability. Currently the so-called “supergrid” is being discussed both in Europe and in the USA.

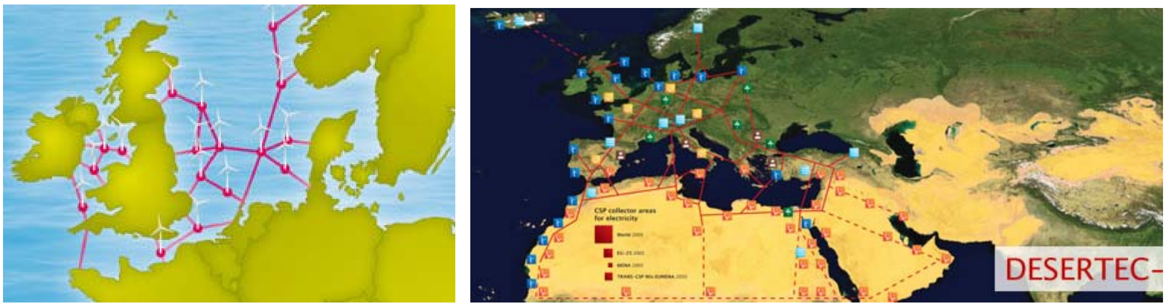


Figure 2: Scheme of discussed topology of HVDC “supergrid” in Europe [6].

As illustrated above, the “supergrid” integrates several wind farms around England and Scandanavia and can support power needs throughout Europe, northern Africa and the Middle East.

SIMULATION EXAMPLE

For the current investigation, the California electrical grid located on the West Coast of the United States was selected for grid simulation due to the variety of energy sources available. All basic data for the installed power plants have been found at the California Energy Commission website [7] and are represented in Figure 3 (left image). Note that for demonstration purposes, the CA grid has been simplified to concentrated producers and consumers.

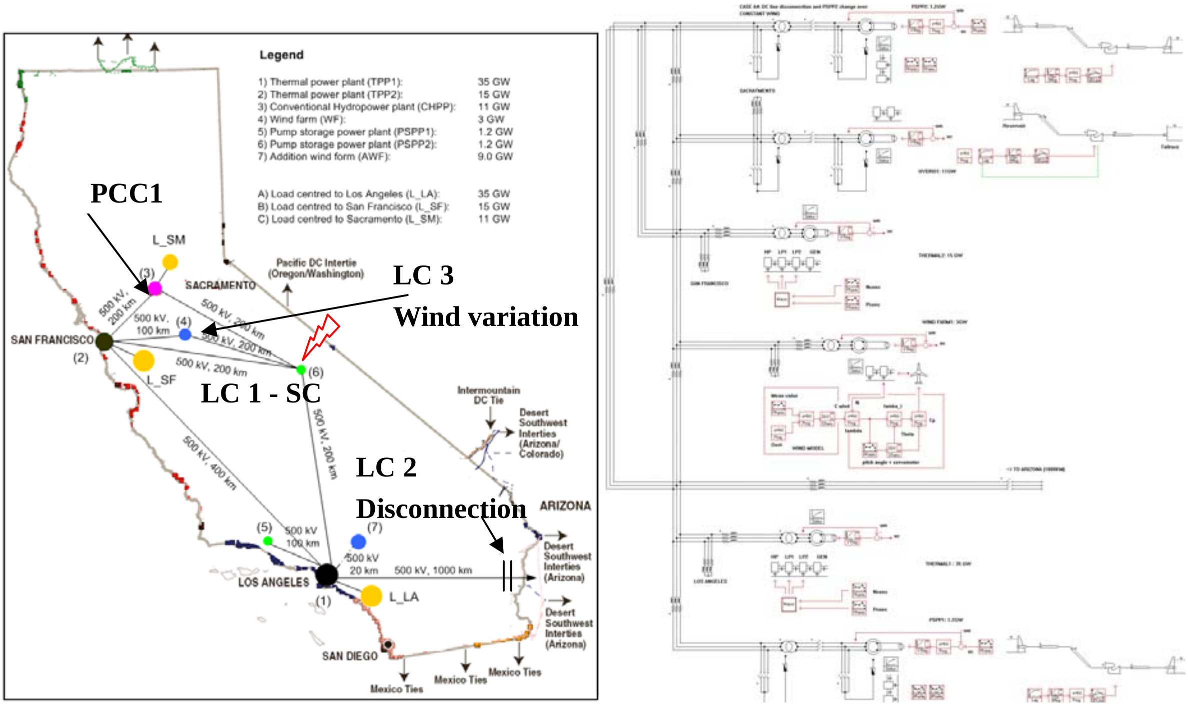


Figure 3: Simplified topology of CA grid (left) and corresponding SIMSEN model (right).

Figure 3 (right image) also illustrates the corresponding electrical network utilized in the simulations. During the current investigation, the grid calculations were performed with SIMSEN which was developed by the EPFL [Ecole Polytechnique Federals de Lausanne, Switzerland] for dynamic simulation and steady state modes of power electrical networks, variable speed drives and hydraulic systems.

The total installed California capacity amounts to approximately 70 GW. Considering typical values for moment of inertia for the individual generating units scaled to 60Hz, the total moment of inertia J^{60Hz}_{total} may be obtained. A simple consideration of a power unbalance (neglecting self-regulating effects and power / frequency control of the power generating units) shows how much time it takes for the grid frequency to reach certain deviation. Grid reaction times for various power unbalances can be determined through Equation (2).

$$\Delta\omega = \frac{\Delta M * \Delta t}{J^{60Hz}_{total}} \tag{2}$$

This overview can be used to estimate how fast the regulating units have to start to in order to control the power and frequency. The reaction times for the California grid to reach 1% and 3% frequency deviation for power unbalances of ΔP = 500, 1000, and 5000 MW are given in Table 1.

Δ P	Δ t (Δf = 1%)	Δ t (Δf = 3%)
500 MW	16 s	48 s
1 000 MW	8 s	24 s
5 000 MW	1.6 s	4.8 s

Table 1 - Reaction times for the grid in considerations reaching 1% and 3% frequency deviation for given active power deficit.

Depending on the expected (considered) sudden power deficit, it may be reasonable to have units with fast starting capability to bring their full power to the grid within less than 1 min.

MODELLING DETAILS

The main concentrated power plants installed within California are (see Figure 3):

- Conventional hydro power plant - 11 GW
- Conventional thermo and gas power plants - 50 GW (35GW + 15GW)
- Pumped Storage power plants - 2.4 GW (2 x 1.2 GW)
- Wind farm - 3GW

The PSPP 2 model was first considered as a fixed speed (SG) unit and then compared with results corresponding to the unit being variable speed (DFIG). For all power plants, standard PID voltage regulators have been considered. Adequate values of the gain of the voltage regulators [8] and power system stabilizers IEEE PSS2B are considered for the hydroelectric power plants to improve the stability of the power network. The structure of the PSS2B [9] is presented in Figure 4. For the purposes of the simulation, the Voltage Source Converters for the variable speed generator have been replaced by a pseudo-continuous model [10], which consists of replacing both voltage source inverters by three controlled voltage sources as represented in Figure 5. This model guarantees that the balances of active and reactive powers are the same as the ones obtained with the complete model and reflects the correct macroscopic behaviour of the generator, without considering higher harmonics due to the PWM modulation. This allowed an efficient simulation by increasing the necessary integration time step, and thus considerably reducing the simulation time.

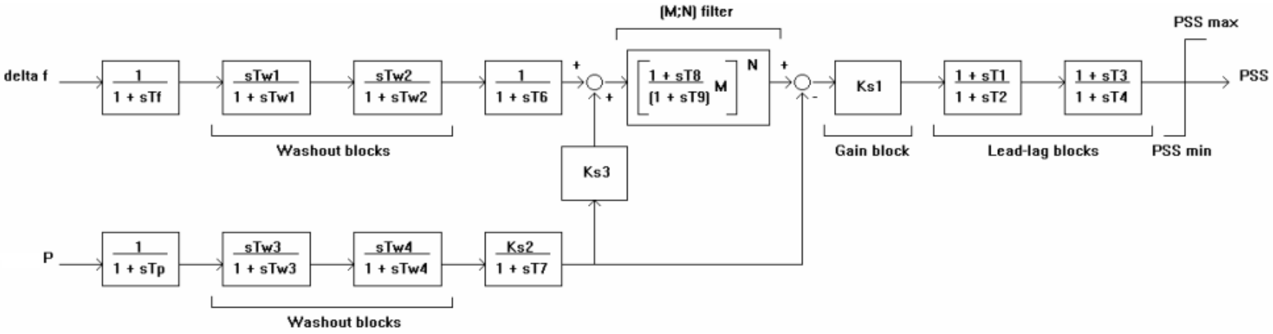


Figure 4: Structure of the power system stabilizer PSS2B.

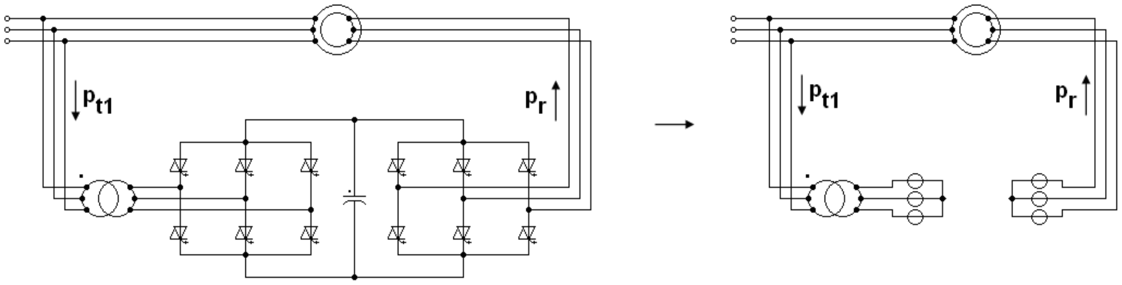


Figure 5: Complete and pseudo continuous models.

All types of power plants have been modelled, including the technological part - hydraulic system and turbine for the water power plant, WTG with pitch control for the wind power, as well as the thermal process for the thermal plants (see [13]). All power plants were considered in power control mode. Transmission line lengths and ratings have been estimated according to data found at the California Energy Commission website [7]. As previously described, all simulations have been carried out using the SIMSEN tool, see [11], [12]

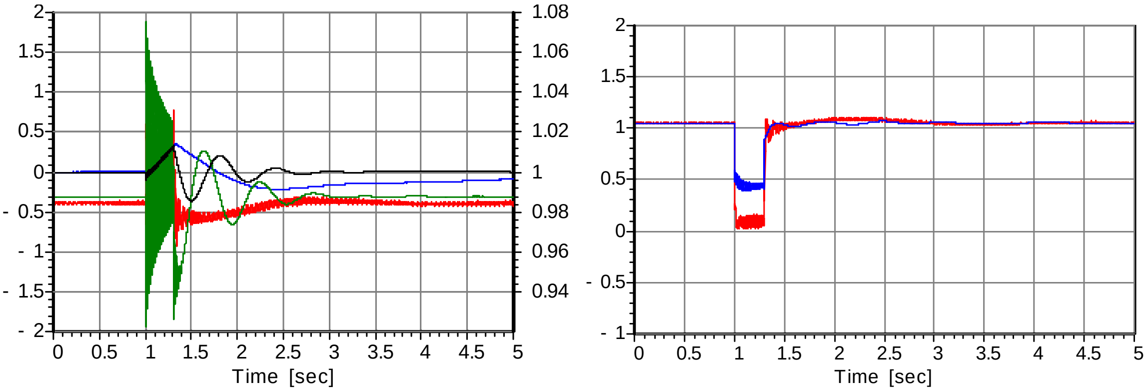
For the current investigation, three separate load cases were considered (see also Fig. 3), including:

(1) 3 phase short circuit close to a PSPP2
(2) disconnection from Arizona, “isolated” operation
(3) variation of wind power

SIMULATION RESULTS

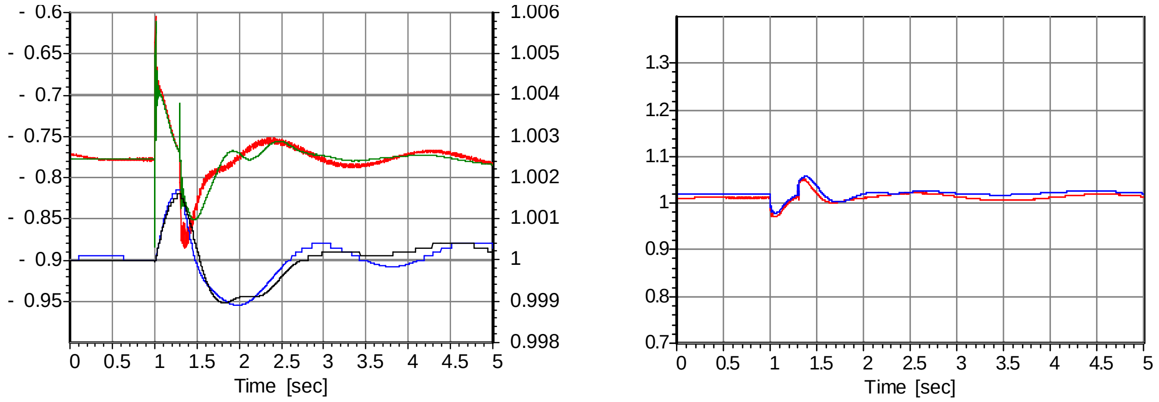
All results are shown in “per unit”, i.e. normalized by specified nominal values for individual quantities.

Load case 1 - Short circuit close to PSPP2



a) b)

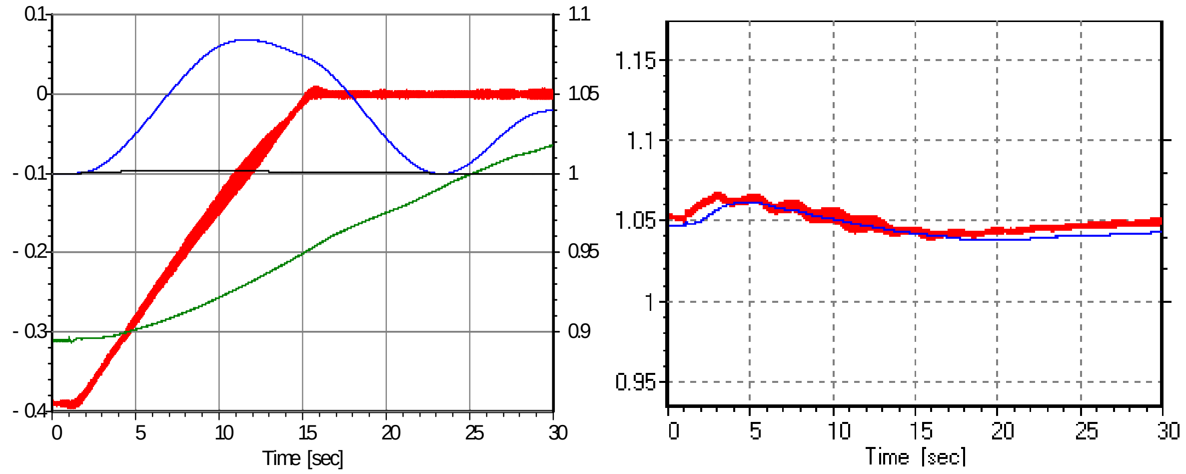
Figure 6: Results at PSPP2: a) left axis - active power (red - DFIG, green - SG), right axis - speed (blue - DFIG, black - SG), b) terminal voltage (red - DFIG, blue - SG).



a) b)

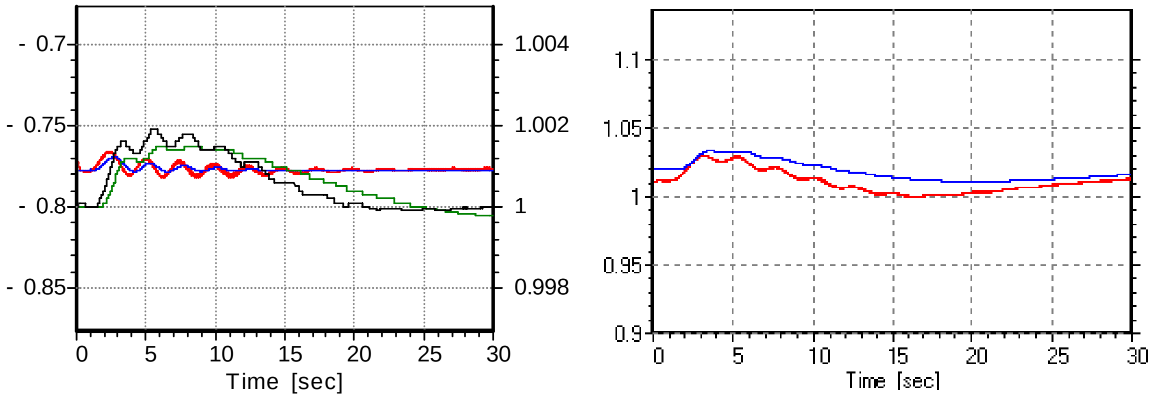
Figure 7: Measurement point at PCC1: a) left axis - active power (red - DFIG, green - SG), right axis - frequency (blue - DFIG, black - SG), b) line voltage (red - DFIG, blue- SG).

Load case 2 - Disconnection from Arizona, “isolated” operation



a) b)

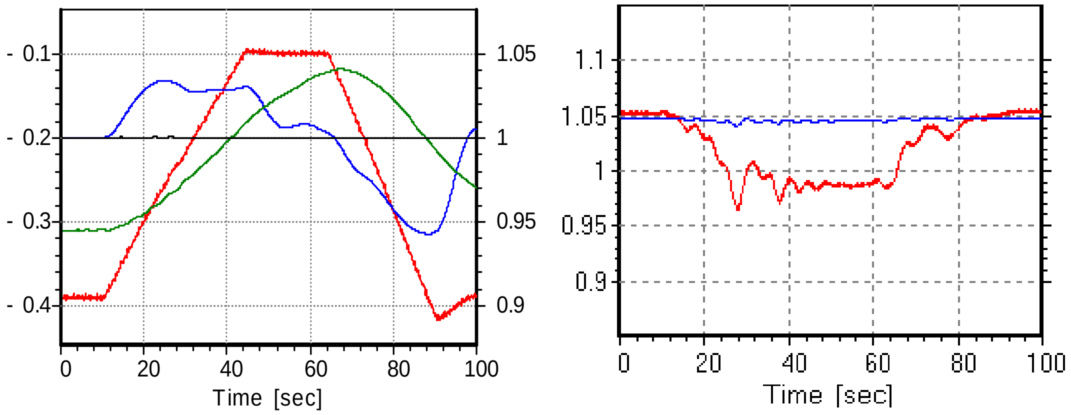
Figure 8: Results at PSPP2: a) left axis - active power (red - DFIG, green - SG), right axis - speed (blue - DFIG, black - SG), b) terminal voltage (red - DFIG, blue - SG).



a) b)

Figure 9: Measurement point at PCC1: a) left axis - active power (red - DFIG, green - SG), right axis - frequency (blue - DFIG, black - SG), b) line voltage (red - DFIG, blue - SG).

Load case 3 - Variation of wind power



a) b)

Figure 10: Results at PSPP2: a) left axis - active power (red - DFIG, green - SG), right axis - speed (blue - DFIG, black - SG), b) terminal voltage (red - DFIG, blue - SG).

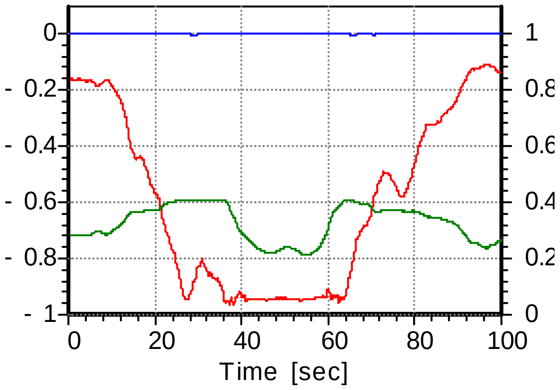
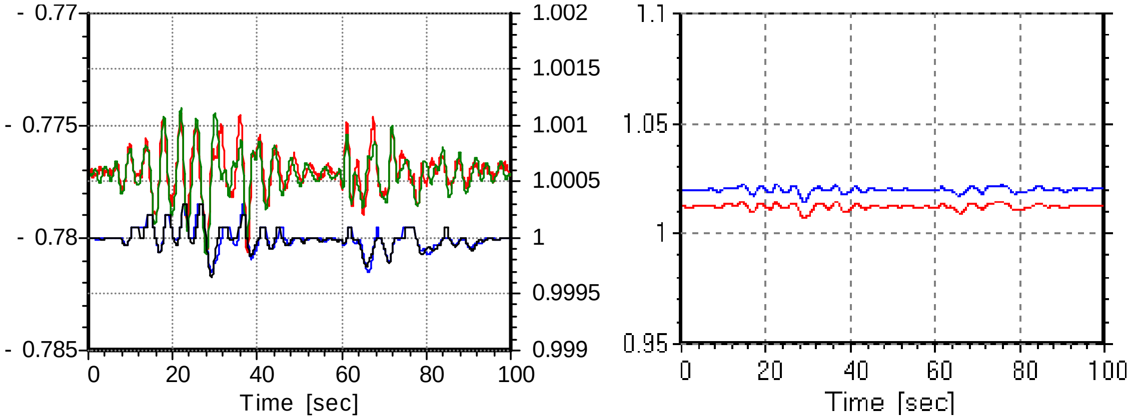


Figure 11: left axis- wind farm active power - red, right axis - Cp - green and speed - blue.



a) b)

Figure 12: Measurement point at PCC1: a) left axis - active power (red - DFIG, green - SG), right axis - frequency (blue - DFIG, black - SG), b) line voltage (red - DFIG, blue - SG).

DISCUSSION OF SIMULATION RESULTS

According to [2], many grid codes allow frequency deviations in the range of -1% to +0.3% without restriction. The simulation results for all investigated load cases clearly show that the variable speed units can reduce oscillations in both voltage and frequency. It should be noted that all the results for the California grid example presented in this paper fulfill current ISO requirements with fixed speed units.

Case 1 (Short circuit close to PSPP2):

For this case, a three phase short circuit is applied at the high voltage side of the step up transformer for 300 ms. The impact of this short circuit on global monitoring point PCC1 and the terminals of the SG and DFIG are shown in the Fig. 7. Both types of generators sustain the short circuit and the global impact on frequency and voltage is within 20 mHz and 5%, respectively.

Case 2 (Disconnection from Arizona, “isolated” operation)*:*

For this simulation, the Arizona line is disconnected at 1 sec, which then isolates the California grid. Before disconnection of the Arizona line, the active power was flowing to the Arizona line. To balance the increment of available active power, the reference power of PSPP2 is reduced to zero within 15 sec. It can be observed in Fig. 8 (left) that DFIG reacts faster due to variable speed as compared to SG. Despite this faster reaction time, there is no remarkable difference in the grid state variables at the PCC1.

Case 3 (Variation of wind power):

The impact of changing wind power on the grid is analyzed in this case. Within 30 sec, the sharp changes in wind velocity shown in Fig. 11 increase wind power from 500 MW to 3 GW (i.e. from -0.16 pu to -1.0 pu). At 65 sec, the wind power is reduced to 300 MW (i.e. to -0.1 pu) within 30 sec. Due to better wind power forecast and direct communication between PSPP and wind farms, it is possible to adjust the reference active power of PSPP. At PCC1, there is no significant change in the grid state variables with both types of the generators.

CONCLUSIONS

This paper shows an example of larger grid simulation, giving an idea about the system reaction to various disturbances including large wind power variations. In the presented simulation, 3 GW of wind power installed capacity has been considered.

Even though the example selected does not show the necessity of installing variable speed pumped storage units, the situation may be different for different grid topology or for increased installed capacity of wind power. According to the information available, there is planned increase of wind installed capacity by 9 GW in the near future in California. For effective and stable operation of large grids, smoothing control techniques for wind farms as well as HVDC grids should be considered.

Using the SIMSEN advanced simulation technology approach and in depth knowledge of pump turbine units as well as control system technologies, Voith Hydro can provide support for analyzing and understanding the grid needs, thus helping to select the optimum technical solution for hydro power plant pumped storage equipment.

REFERENCES

[1] Iov, F. et.al.: *Mapping of grid faults and grid codes*, Riso, Technical University of Denmark, 2007.

[2] Sangroniz, N. et.al.: *Review of International Grid Codes for Wind Generation*, Congress CBQEE VIII, 2009

[3] Hodder, A.: *Double-fed asynchronous motor-generator equipped with a 3-level VSI cascade*, PhD Thesis No. 2939, École Polytechnique Fédérale de Lausanne, 2004.

[4] Koutnik, J. et.al.:*Pump-Storage with adjustable speed – Simulative comparison of different variants,* HydroVision 2008

[5] Clemow, P.: *Wind Farm Output Smoothing Through Coordinated Control*, 3rd EPE Wind Energy Chapter Seminar, Stafford, 2010

[6] Davidson, C.: *The Importance of Power Electronics for Wind Power and other Renewable Energy Sources,* 3rd EPE Wind Energy Chapter Seminar, Stafford, 2010

[7] www.energy.ca.gov

[8] Kawkabani, B.: *Extension of the complex torque coefficient method for synchronous generators to auxiliary devices in electrical networks*, 9th European Conference on Power Electronics and Applications (EPE'2001), Graz (Austria), 2001.

[9] Kamwa, I., Grondin, R., Trudel, G, *IEEE PSS2B Versus PSS4B: The limits of Performance of Modern Power System Stabilizers*, IEEE Transactions on Power Systems, Vol. 20, No 2, May 2005.

[10] Pannatier, Y., Kawkabani, B., Sari, G., Simond J.-J., *Stability studies of a mixed islanded power network with Varspeed units using simplified models of the converters*, ECCE 2010, IEEE Energy Conversion Congress and Exposition, September 12-16, 2010, Atlanta, Georgia, USA

[11] Simond, J.-J., Allenbach, P., Nicolet, C. and Avellan, F.: *Simulation tool linking hydroelectric production sites and electrical networks*, Proceedings of the 27th Int. Conf. on Electrical Machines, ICEM, Chania, Greece, September 2-5, 2006

[12] Nicolet, C., Sapin, A., Simond, J.-J., Prenat, J.-E. and Avellan, F.: *A new tool for the simulation of dynamic behaviour of hydroelectric power plants*, Proceedings of the 10th International Meeting of WG1, IAHR, Trondheim, Norway, June 26-28, 2001

[13] Nicolet, C., Greiveldinger, B., Hérou, J.-J., Kawkabani, B., Allenbach, P., Simond, J.-J., Avellan, F., *High Order Modeling of Hydraulic Power Plant in Islanded Power Network*, IEEE Transactions on Power Systems, Vol. 22, Number 4, November 2007, pp.: 1870-1881.

[14] Nicolet, C., Vaillant, Y., Kawkabani, B., Allenbach, P., Simond, J.-J., Avellan, F., Pumped Storage Units to Stabilize Mixed Islanded Power Network: a Transient Analysis , Proceedings of HYDRO 2008, October 6-9, 2008, in Ljubljana, Slovenia, Paper 16.1.

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Basile Kawkabani received his master degree in 1978 from SUPELEC, Ecole Supérieure d’Electricité in Paris France, and his Ph.D. degree in 1984 from the Swiss Federal Institute of Technology in Lausanne Switzerland. Since 1990, he is lecturer and senior researcher at the EPFL Electrical Machinery Laboratory. His interests include modeling of power systems, power system stability and control.

Christophe Nicolet graduated from the Ecole polytechnique fédérale de Lausanne, EPFL, in Switzerland, and received his Master degree in Mechanical Engineering in 2001. He obtained his PhD in 2007 from the same institution in the Laboratory for Hydraulic Machines. Since, he is managing director and principal consultant of Power Vision Engineering Sàrl in Ecublens, Switzerland. He is also lecturer at EPFL in the field of “Flow Transients in Systems”.