STABILITY OF THE POWER SYSTEMS IN CASE OF LARGE WIND PENETRATION AND BATTERY APPLICATION

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Abstract – In this paper the application of batteries for the increase of the stability of a power system with high penetration of wind power is presented. The increase of the wind power penetration in power systems causes changes in power system operation, i.e. in its stability. The behaviour of the system with large wind penetration in case of wind farm disconnection has been simulated and its stability analysed. The impact of the battery application has shown that the stability of the system is significantly improved and the system operation is not in danger.

The impact of the wind power fluctuations on the power system stability has also been analysed. The application of the battery diminishes the fluctuations of the power output and the operation of the system becomes much more stable.

Keywords:* *Wind, offshore, storage, battery, stability.

1 INTRODUCTION

In the last decade we are witnessing a very fast increase of the renewable energy sources, especially wind. Only in Germany is expected more than 50 GW of installed wind capacity until 2020. Due to lack of suitable places onshore and much better wind conditions more than 20 GW (Figure 1) are planned to be built offshore (North and Baltic Sea [1]).

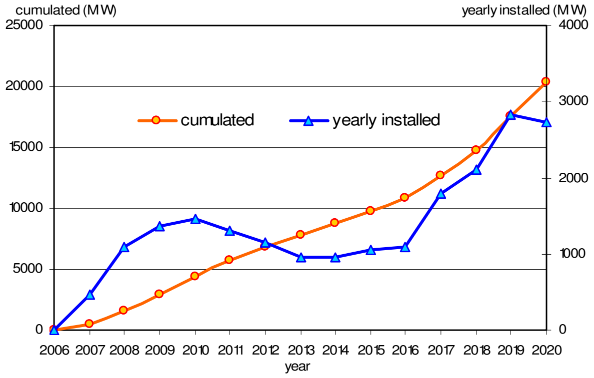

Figure 1: Planned offshore wind power capacity in Germany until 2020

However, the volatility of the wind, its large fluctuations and still no accurate wind forecast make its integration into the power system difficult. After commissioning of the planed offshore wind farms these problems will become more severe, since their connection will be on a relatively short coast line. Two main solutions for solving these problems are:

- improved wind forecast,
- introducing energy storage.

As one of the most promising technologies, the use of batteries as wind energy storage is analysed. The principle of the connection of the wind farm and battery is shown in Figure 2.

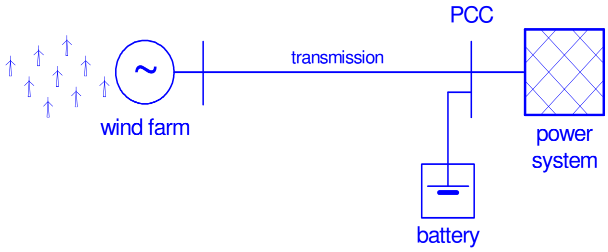

Figure 2: The principle of the connection of the wind farm and battery

The battery application can be divided into the following tasks:

- power application (from milliseconds up to several minutes), where the use of the battery is primarily as ancillary service for the wind farm and, also, for the power system. This includes the primary and secondary control power of the wind farm, mitigation of power fluctuations from the wind farm etc.
- energy application (hours up to several days), where the battery can be used for peak shaving, congestion management, avoiding equipment overloading (asset management) etc.

Recently, a market application, which technically has no differences to the power or energy applications, is becoming interesting. Here, the battery can be used for trading with stored wind energy (power) at the electrical or at the ancillary service market (primary, secondary and minute control power reserve).

Until now the large batteries are mostly used for energy application (peak shaving, load shifting, power backup, reliability etc.) with continuous and rapid increase of their installed power [2].

Due to already mentioned problems with wind power volatility, the application of batteries for their solving is very interesting. As an additional benefit, the application of the batteries for improving the stability performances of the power system will be analysed here.

2 NAS BATTERY AND ITS ELECTRICAL MODEL

In [3] sodium sulphur batteries (NAS) have been recognised as very good for the application in power systems. This is due to their high power and energy density, large power capacity, efficiency (up to 90%) and relatively long life time (15 years or 2500 full cycles). A very important characteristic of the batteries is their very fast acting time, i.e. when needed, they connect very fast to the system. Furthermore, due to a large pulse power factor (Figure 3), they are able to feed into the system very high amount of power for a short time.

On the other side, the NAS battery is rather expensive at the time. However, with the cognition of the storage importance for the power systems, the research in this area will push the manufacturers to more competitiveness and lead to their lower costs. This is especially in case when the technology is still not mature.

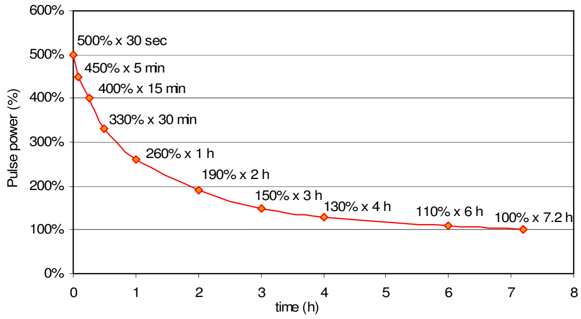

Figure 3: Pulse power vs. pulse duration of NAS battery [3]

According to [4], if fully loaded, the NAS battery is able to supply the system with 400% of its rated power for 15 minutes. This is a large advantage of NAS batteries and together with fast access time it can play a very important role for the power system stability and control.

In order to implement the battery in power simulations, the equivalent circuit of the battery is needed. There are many proposed models:

- ideal - the battery is represented as an ideal voltage source without any resistances,

- linear - where the internal resistance of the battery is being considered,

- Thevenin model - beside the internal resistance an overvoltage component is included too (parallel combination of capacitance and resistance).

For most cases these models are sufficient to model the battery in power system simulations. However, the NAS battery has a specific pulse power characteristic which enables the charging/discharging of the battery with much higher power than the rated one (Figure 3). Therefore the internal resistances of the battery are not linear in the model, i.e. they are in correlation with the pulse power characteristic. In [5] an improved model of the battery which considers the specific characteristics of the NAS battery has been introduced. This model can be further refined for the purpose of more accurate calculations. The modified Thevenin model of the NAS battery is shown in Figure 4.

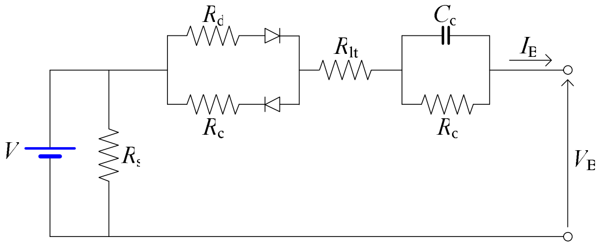

Figure 4: Modified Thevenin model of the NAS battery

This model contains following elements: R_s (self-discharging resistance), R_d (discharging resistance), R_c (charging resistance), R_{lt} (life-time resistance), C_o (capacitance for overvoltage component), R_s (resistance for overvoltage component), V (internal voltage), V_B (output voltage of the battery) and I_B (current of the battery). It has to be mentioned, that these parameters are not constant, i.e. they depend on many factors such as: state of charge of the battery, temperature, age etc. Therefore, every battery station can have different parameters. Due to the low self-discharging rate, long life-time and almost constant temperature (operating temperature 300-320^{o}C), for the purpose of the simulations presented in this paper, these elements can be neglected.

The battery is connected to the system via a power converter system (PCS) which is using IGBT transistors. This enables the use of pulse width modulation for the control of the battery and its connection to the system (Figure 5).

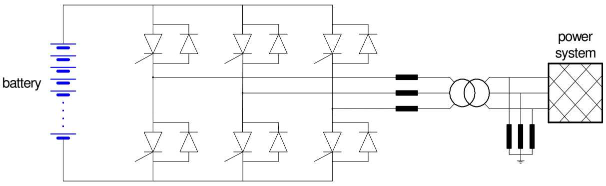

Figure 5: The connection of the battery to the system with PCS

3 APPLIED SYSTEM

In this paper the focus is made on the power application of the battery, where the stability of the system will be analysed. In order to analyse the impact of the battery storage on a power system with large amount of wind power a nine bus test system [6] is modelled (Figure 6).

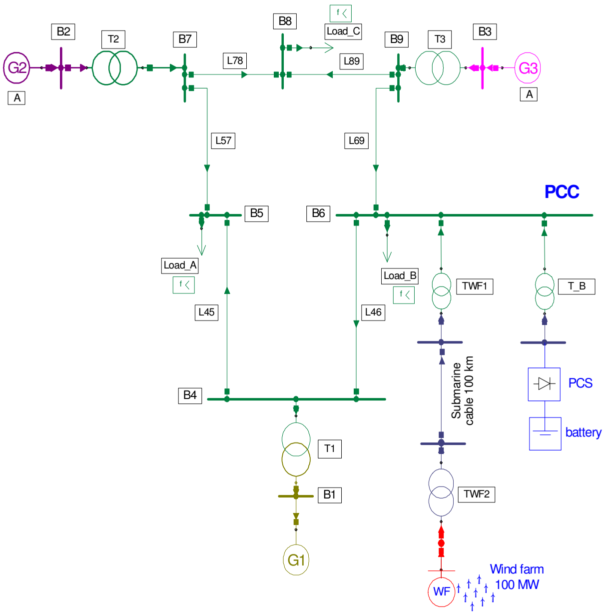

Figure 6: Modelled system with wind farm and battery in NEPLAN®

The system has 3 synchronous generators with total installed power of 567,5 MVA, 3 loads with total installed power of 315 MW (115 Mvar) and 5 lines which are connecting 6 busses. A 100 MW wind farm is connected at the busbar B6 (PCC) and it supplies almost 30% of the load demand. Therefore the system can be regarded as a system with large wind penetration. This model can also be considered as a possible, very simplified, scenario of the future German power system with large offshore wind farms in the north of the country. At the PCC the battery with rated power of 25 MW is connected. The size of the battery has been chosen to meet the demands of the secondary power control for a wind farm, i.e. it can supply 100 MW (400% of rated power of battery) for 15 minutes. Therewith the UCTE requirements regarding power system control [7] are met. The model has been built in the power system software tool NEPLAN®.

4 SIMULATION

The behaviour of the system with large wind power penetration has been analysed for the following two situations: disconnection of a whole wind farm and wind power fluctuations.

4.1 Disconnection of a whole wind farm

Here three cases have been modelled: base case, case with controllable loads and case with battery.

A. Base case

As a most severe possible disturbance for the system, a disconnection of a whole wind farm is analysed. The disconnection (due to wind storm, failure…) occurs at *t*=2 s. The frequency and voltage at the PCC and the active power of all generators are shown in figures 7, 8 and 9 respectively.

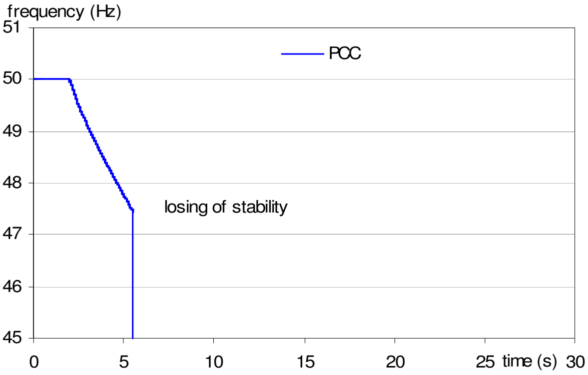

Figure 7: Frequency at PCC - base case

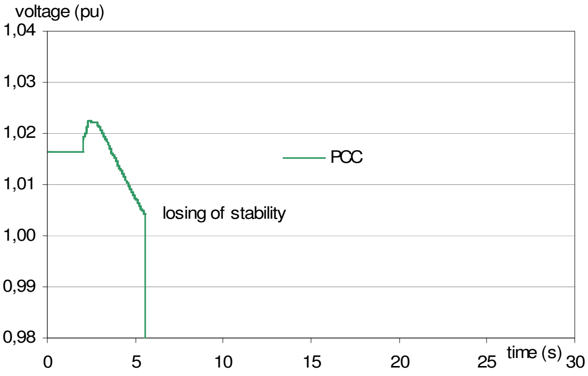

Figure 8: Voltage at PCC - base case

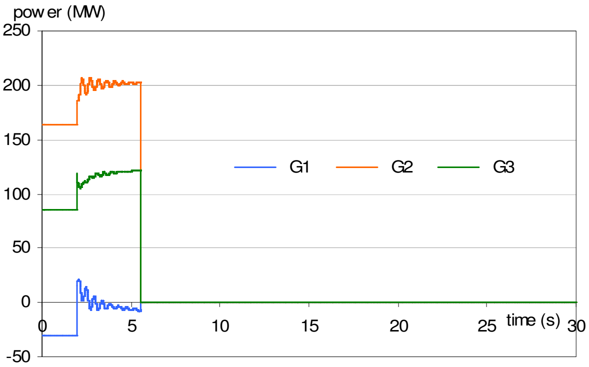

Figure 9: Active power of generators G1-G3 - base case

It is obvious from these figures that the system can not maintain its stability. Shortly after disconnection of the wind farm the frequency is dropping. The generators are trying to cover the loss of the wind power and they are increasing their power contribution to the system. However, the frequency continues to decrease and in *t*=5,44 s it reaches *f*=47,5 Hz when the generators are being disconnected from the system, i.e. the system becomes instable.

B. Controllable loads

For this case there is a possibility to control the loads according to the UCTE requirements [7]:

- 49,0 Hz - shedding of 10-15% of the load
- 48,7 Hz - shedding of further 10-15% of the load

- 48,4 Hz - shedding of further 15-20% of the load
- 47,5 Hz - disconnection of the generators from the grid.

In figures 10, 11, 12 and 13 the simulation results for the system with controllable loads are presented. Namely, the loads are set to shed 12,5% of their active power at 49 and 48,7 Hz, further 17,5% at 48,4 Hz and to be entirely disconnected at 47,5 Hz.

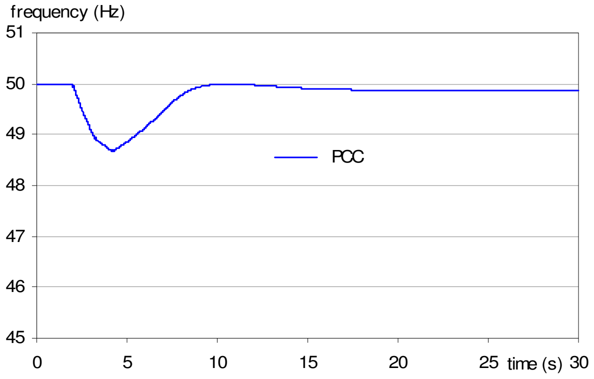

Figure 10: Frequency at PCC - controllable loads

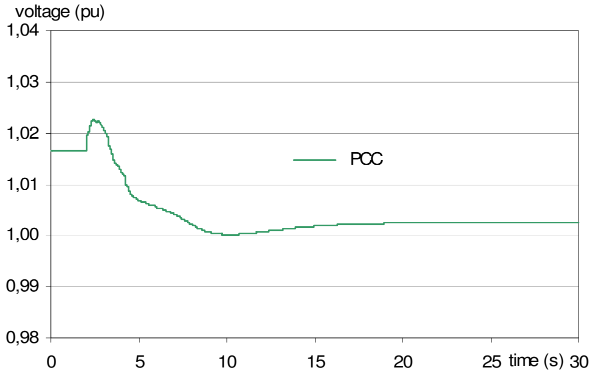

Figure 11: Voltage at PCC - controllable loads

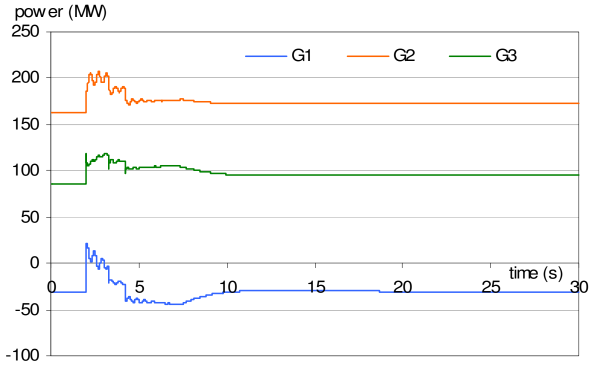

Figure 12: Active power of generators G1-G3 - controllable loads

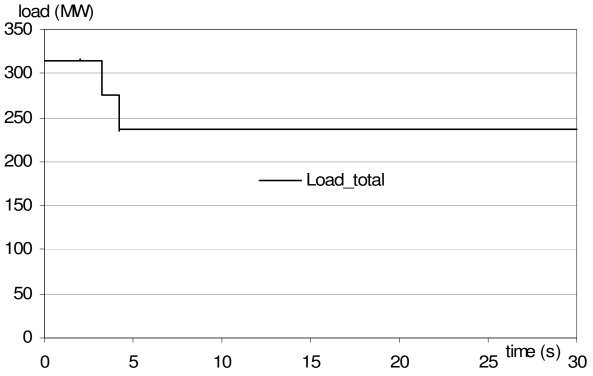

Figure 13: Total load of the system - controllable loads

As it can be seen, the behaviour of the system is identical to the previous case until *t*=3,25 s when the frequency of the system reaches 49 Hz. At this point 12,5% of the loads A, B and C are shedding. However this shedding is not enough to keep the system in stable operation and the decrease of the frequency is continuing. After reaching 48,7 Hz further 12,5% of the loads A, B and C are shed. With this action the frequency drop is stopped and recovers fast to the nominal 50 Hz - the system maintains stable operation. However, the price is the disconnection of 25% of the entire load!

To evaluate the impact of the wind farm size, i.e. its power output on the system stability, in Figure 14 the frequencies of the system in case of disconnection of wind farms with power output of 50 and 10 MW are shown.

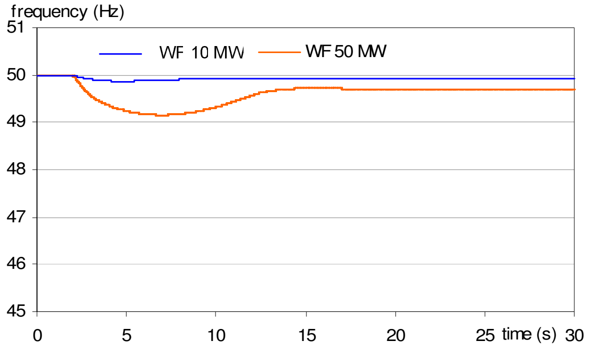

Figure 14: Frequency at PCC for 50 and 10 MW wind farm power output

It is clear that in these cases the system remains stable. The synchronous generators are able to supply missing power. According to the previous cases and this one, it is obvious that in case of wind farm disconnection the stability of the system increases with a decrease of the wind power penetration.

C. Battery backup

In this case a NAS battery is being used as a backup of the wind farm. After disconnection of the wind farm at *t*=2 s, the battery is connected to the system at *t*=2,2 s. The behaviour of the frequency, voltage, and active power of the generators are given in figures 15, 16 and 17 respectively.

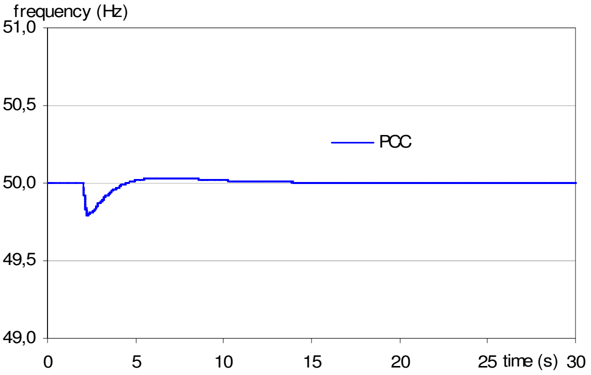

Figure 15: Frequency at PCC - battery backup

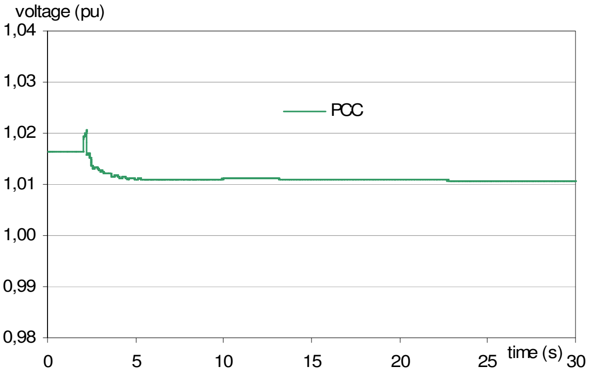

Figure 16: Voltage at PCC - battery backup

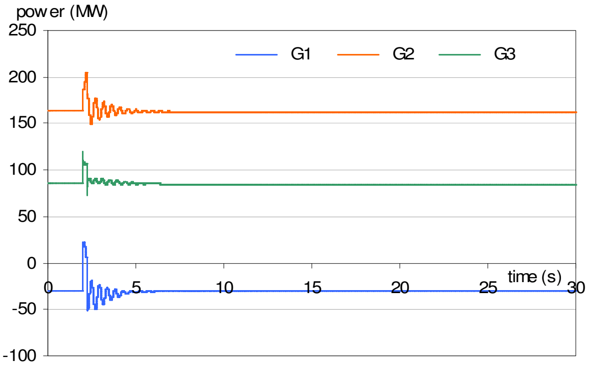

Figure 17: Active power of generators G1-G3 - battery backup

It is obvious that the system retains its stability when supported by the battery. Since the battery can be used very fast (in the given case 200 ms after the disturbance occurred), the frequency is dropping only by 0,2 Hz and it is returning to a steady state. After a maximum of 15 minutes some other source from the minute reserve should be connected to the system and secure the stable operation of the system for a longer time.

To compare all three cases the behaviour of their frequencies are given in Figure 18.

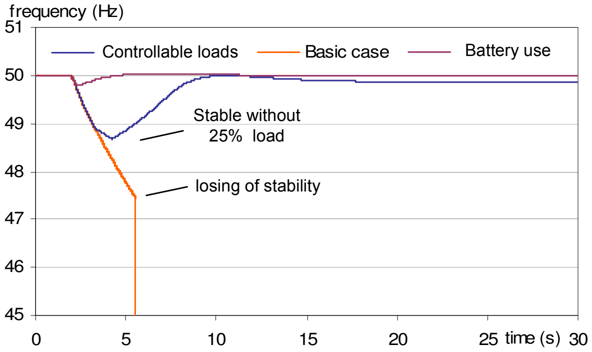

Figure 18: Frequencies for all three cases

In the base case the system is not reaching the stable operation point, i.e. the disturbance is too severe and the system becomes unstable after a very short time. If the system is equipped with controllable loads it is possible to keep the system operation stable. However, this means that a part of the consumer load (25%) has to be disconnected, which is not desirable. With the use of the battery the system has no problem keeping the system operation stable.

4.2 Wind power fluctuations

Due to the wind speed fluctuations, the power output of a wind farm can also have large fluctuations [8]. These wind farm power fluctuations can cause frequency deviations in the system and, therewith, the operation of the synchronous generators are exposed to fluctuating power generation. In Figure 19 a modelled wind pattern and corresponding power output from a wind farm are given.

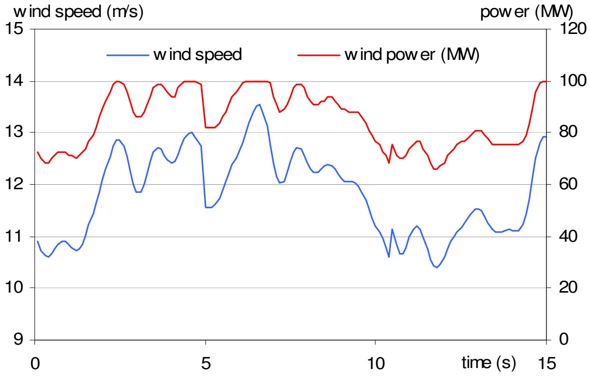

Figure 19: Wind pattern and corresponding power output from a 100 MW wind farm

The average wind speed is v_{av}=11,8 m/s with a maximum of 13,5 m/s and a minimum of 10,4 m/s (fluctuations up to 14%). According to a typical power curve of a wind generator [8], the corresponding power output of a 100 MW wind farm has an average active power of P_{wf_av}= 85 MW with a maximum of 100 MW and a minimum of 66,1 MW (power fluctuations up to 22%). The behaviour of the system (frequency and active power of the generator G3) is given in Figure 20.

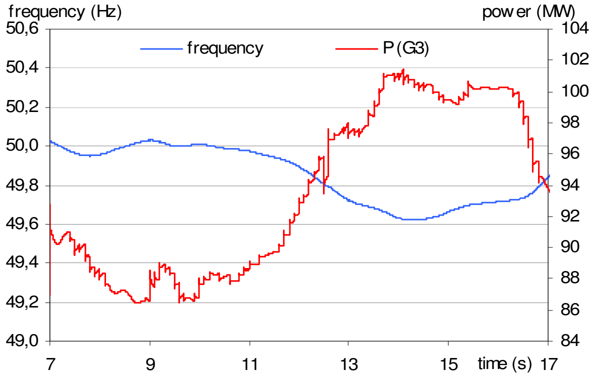

Figure 20: Frequency at PCC and active power of G3 in case of wind power fluctuations - without battery

Although the system is not becoming instable, there is a large fluctuation of the frequency. In the given case it is dropping to almost 49,6 Hz. Since the generators are working as a backup of the wind farm and trying to keep the system stable, they operation is highly stressed. The oscillation of active power of the generator is from 86-102 MW. That means that the wind power fluctuations have large and negative impact on the system.

To avoid these problems a battery can be used. In figures 21 and 22 the system behaviour in case of wind fluctuations and use of the battery is shown. The frequency of the system and active power of the generator G3 are shown in Figure 21. The power output from the wind farm, battery and the resulting power output at the PCC are given in Figure 22.

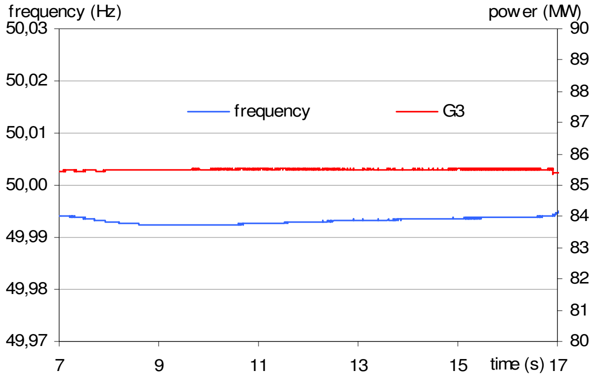

Figure 21: Frequency at PCC and active power of G3 in case of wind power fluctuations – with battery

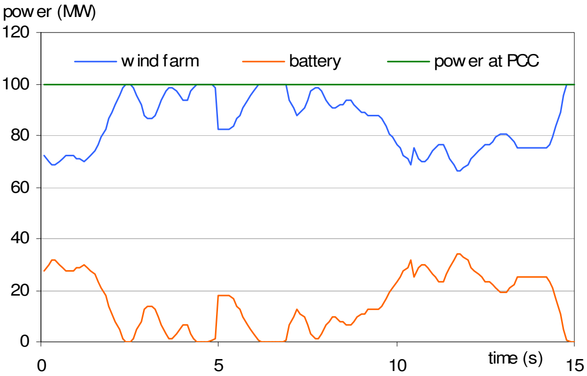

Figure 22: Power of the wind farm, battery and at the PCC

The power at the PCC is constant since the battery compensates for the missing power from the wind farm. For the given case the power output of the "wind farm - battery" was set to 100 MW. The generator G3 has almost no fluctuations and the frequency is nearly constant. With the use of the battery, the system behaviour is much more stable, i.e. the system shows insensibility to the wind power fluctuations.

5 CONCLUSION

From technical point of view the application of batteries as a backup of wind power generation can be very advantageous. In case of a wind farm disconnection the system can lose its stability or is forced to shed a part of the load to maintain its stability. With batteries applied, the system remains stable and, therefore, the battery can be used for primary and secondary control for the wind farm and for the entire system too. Furthermore, the negative influence of the wind power fluctuations on the system can be diminished when using batteries. With the increase of the wind penetration the stability of the system is more jeopardized and the importance of a possible battery use increases.

6 REFERENCES

[1] German Energy Agency (dena), "Integration into the national grid of onshore and offshore wind energy generated in Germany by the year 2020", Berlin, Germany, 2004

[2] J. A. McDowall, "Status and Outlook of the Energy Storage Market", IEEE Power Engineering Society General Meeting, Tampa USA, June 2007

[3] E. Spahić and G. Balzer, "The Application of Batteries as a Backup of Large Wind Farms", Large Scale Integration of Wind Power and Transmission Systems for Offshore Wind Farms, Paper No. 43, Delft, The Netherlands, October 2006

[4] M. Kamibayashi, D. K. Nichols and T. Oshima, "Development update of the NAS Battery", in Proc. IEEE/PES Transmission and Distribution Conference and Exhibition, Yokohama, Japan, vol. 3, pp. 1664 – 1668, October 2002

[5] Z.F. Hussien, L.W. Chung, M.F.M Siam and A.B. Ismail, "Modelling of Sodium Sulfur Battery for Power System Applications", Elektrika Journal of electrical Engineering, Vol. 9, No. 2, 2007, pp 66-72

[6] P.M. Anderson and A.A. Fouad, "Power System Control and Stability", 2nd Edition, John Wiley & Sons Inc., 2002

[7] UCTE, "UCTE Operation Handbook", Brussels, Belgium 2004

[8] E. Spahić and G. Balzer, "The Impact of the Wind Farm Size on the Power Output Fluctuations", European Wind Energy Conference EWEC 2006, Athens, Greece, Feb/Mar 2006