Battery Storage System for Frequency Stabilization of AC Networks with High Penetration of Renewable Power

Giddani O. A. Kalcon
Abdelaziz Y. M. Abbas
School of Electrical and Nuclear Engineering,
Sudan University of Science and Technology, Khartoum, Sudan
Ganio101@yahoo.com
abdelaziz.abbas@yahoo.com

Abstract: This paper investigates the uses of battery energy storage system (BESS) in ac networks highly populated with wind power generation. The investigation includes power system load levelling, frequency stabilization, and provision of reactive power support to the wind farm network. The BESS is connected to the wind farm main hub via voltage source converter, while the wind farm is connected to ac network modelled with detailed synchronous generator, including excitation and turbine-governor control. In general the paper attempted to study the role of BESS in modern power system regarding improving system stability. Time-domain simulations conducted in Matlab/Simulink are used to validate the importance of the BESS.

Index Terms: *Battery energy storage system, Frequency stability, Renewable energy recourse, and voltage source converter.*

المستخلص: هذه الورقة تتحدث عن استخدام بطاريات تخزين القدرة الكهربائية في انطمة القدرة الكهربائية التي تحتوي علي محطات الرياح. الدراسة تشمل توازن الاحمال الكهربائية استقرارية التردد و تعويض القدرة الردفعلية عند قضبان تجميع محطات الرياح. وصلت بطاريات تخزين القدرة الكهربائية الي محطات الرياح خلال مبدل الجهد المصدري بينما وصلت محطات الرياح الي نظام قدرة ممثل بمولد تزامني متكامل يشمل انظمة تحكم الاثارة والتوربينات. تهدف الورقة لدراسة دور بطاريات تخزين القدرة الكهربائية في تحسين استقرارية النظام باستخدام برنـامج المحاكاة (Matlab/Simulink).

Introduction:

During the recent years, renewable power generation received a considerable attention due to the global concerns associated with clean/green energy and potential worldwide energy shortages. Electricity generation from solar and wind energies are the most mature technologies among the other forms of the renewable energies. The penetrations of power from these sources have increased significantly in the last decade. This introduces significant challenges to the control of the ac networks in the past dominated by synchronous generators and now populated with different types of generating units such as doubly fed induction generator (DFIGURE), fixed speed induction generator (FSIG) and power electronics interfaced wind turbine generators with fully rated converter and photovoltaic systems[1, 5].

In power systems the active power balance is strongly coupled to the frequency. Any mismatch between generation and demand causes the system frequency to rise or decrease, depending on the net difference between generation and demand. The nature of the wind power introduces new challenges for power system operators regarding the power levelling during wind power variation. Therefore, the need is arise for using effective power storage systems coupled with wind power farms in order to ensure the system power balance and maintain constant frequency. Recently large increase in the use of power electronics interfaced generations with approximately zero inertia significantly affect the way the ac networks respond to active power mismatch and sub-synchronous oscillations.

There are several studies in the open literature to improve the performance of load frequency control (LFC) during power imbalance due to any reason such as renewable power variations or sudden load change. The usage of energy storages such as Battery, flywheel, pumped hydro, compressed air and super capacitor systems represents one of the attempts to improve the performance of LFC during peak load period. The authors in [6] have studied the effect of 30 MW batteries on the frequency regulation in the Israeli isolated power system. Their study was performed on a single area model representing the whole power system and containing a first order transfer function that represented the BESS performance. However, they have not considered the effect of generation rate constraints on dynamic performances. Also the authors in [7] have studied the effect of BESS on two area system considering conventional tie-line bias control strategy. The study reveals that a BESS with simple control can effectively reduce frequency and tie-line power oscillations following sudden small load disturbances.

Aditya in [8] proposed an incremental BESS for two area interconnected reheat thermal system. The BESS is connected to the system via conventional current source converter to improve tie-line control strategy with 3% generation rate constraint. The obtained results show that with the use of BESS, the dynamic performance of LFC can greatly improve the overshoots of frequency deviations, tie-power deviation and reduce the steady state values of time error and inadvertent interchange accumulations.

Also there are many researchers investigated the possibility of equipping wind turbine generators such as DFIGURE with additional functionalities, such as ac network frequency stabilization and damping of power oscillations [9, 10].

Battery energy storage system is considered in this paper because it has a potential to become a dominant energy storage means for electric vehicles, large solar and wind farms. For example the additional wind energy generated when wind speed increased could be stored in the batteries and released during peak load demand. The use BESS with wind farms may allow them to behave as virtual power plant capable providing all the functionalities of conventional power plant but with faster dynamic response.

Battery Energy Storages Systems:

Several battery energy storage technologies are already used in power systems to provide ancillary services such as frequency and damping support, load levelling and for other power quality purposes [11, 13]. The batteries used to convert the chemical energy into electrical energy and vice versa. The desired battery voltages as well as current levels are obtained by connecting the cells in series and/or parallel. Different types of batteries have being developed to be used in power system with energy capacity rating from 17-40 MW such as Lead acid, Sodium suphur (Nas), Lithium ion (Li ion), Metal air and Flow batteries. The lead-acid battery is the oldest, cheapest and most proven technology, which has been used for majority power system applications. The Li-ion batteries get the potentials for future development and optimization. The Li-ion batteries have small size, low weight, highest energy density and storage efficiency. The drawback The Li-ion batteries are high cost, contain toxic heavy metals and suffers from severe self-discharge.

The metal–air batteries have low cost and high energy densities but are very difficult to be recharged. The flow batteries are also promising for applications which require long duration storages due to its non-self-discharge capability. A major drawback of the flow battery system is the high cost associated with the operation of a chemical plant involving pump systems, flow control with external storage [14].

The main challenge is how to interface the BESS with the mainland system and control the power flow from or to the storage system. In this case the BESS is provides with control system to achieve the multi-function and increase system controllabilities. Many control system techniques are proposed in order to control BESS. All techniques are designed to directly achieve power levelling, improve system security, peak load shaving and frequency stabilization. Meanwhile indirect additional functionalities can be achieved such as providing reactive power control at the point of the common coupling (in this case the BESS act as SVC or STATCOM).

Test System for the Battery Storage System:

In order to investigate the use of BESS for stabilization of relatively small AC networks with high penetration of wind power, the system in Figure 1 is simulated. G_1 represents 2400MVA steam driven power plant based on synchronous generator modelled with excitation and turbine governor systems. G_2 represents medium-scale wind farm (350MW) based on fixed speed wind turbine generator that uses squirrel cage induction generator. Battery storage system is connected at the wind farm terminal to provide necessary reactive support to the wind farm, loading levelling and frequency support to the AC network. The BESS is connected to 33kV AC bus within the wind farm through voltage source converter with bidirectional power flow capability. The wind farm is connected to the AC network using 275kV AC transmission lines. The wind farm and the synchronous generator feed static load connected to B_1 (S_{L1}=2300+190) MVA. S_{L2}=180+115MVA is additional load connected to B_1 through circuit breaker. The system parameters are shown in Figure 1.

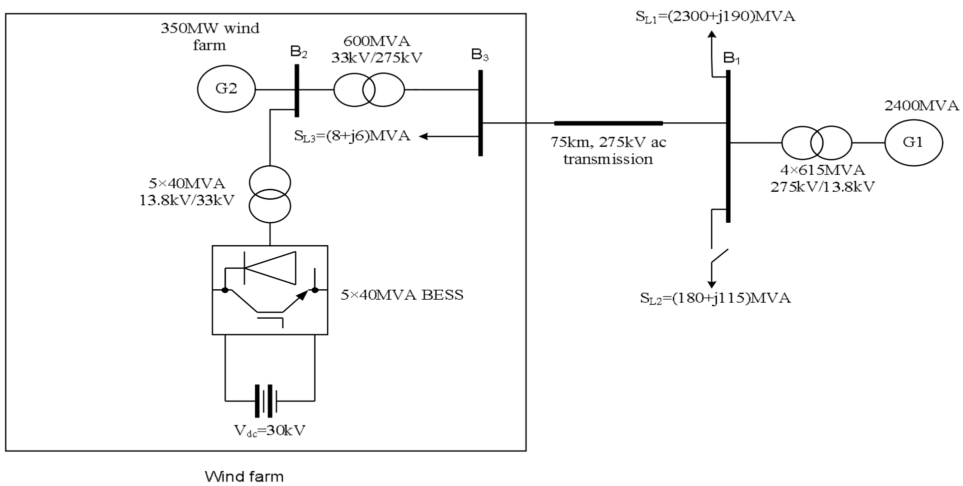


Figure 1: Test system depicting the use of battery storage system for wind farm grid access and stabilization of the ac network with high penetration of wind power

Battery Storage Control System:

BESS achieves power levelling and stabilizes AC network frequency though adjustment of its output active power exchanges with the AC network. Also it can present electronic (synthetic) inertia to AC network in order to damp low frequency power oscillation using active power or DC link voltage modulation. The BESS can be connected to system via AC/DC converter (either conventional current source converter or through voltage source converter).

The connection of BESS using voltage source converter add additional unique control features beside frequency stabilization and power levelling such as voltage regulation and reactive power compensation because the voltage source converter could operate at lead and lag power factor. In this paper the power electronic converter used for interfacing of BESS is configured to act also as STATCOM in order to regulate AC voltage in addition to stabilize the system frequency, and to restraint the AC current injection to the ac network during disturbances. The AC current controller used is designed in synchronous reference frame using VSC AC side dynamic equations [15, 16].

$$\frac{di_{sd}}{dt} = -\frac{R_t}{L_t} i_{sd} + \frac{V_{cd} - V_{sd} - \omega L_t i_{sq}}{L_t} \qquad (1a)$$

$$\frac{di_{sq}}{dt} = -\frac{R_t}{L_t} i_{sq} + \frac{V_{cq} - V_{sq} - \omega L_t i_{sd}}{L_t} \qquad (1b)$$

Where R_t and L_t are the total resistance and inductance of the coupling transformer and interfacing reactor, respectively. V_{sd} and V_{sq} are the direct and quadrature axis system voltages, V_{cq} and V_{cq} are the direct and quadrature axis converter voltages while i_{sd} and i_{sq} are direct and quadrature axis converter current.

Assume $V_d = (\omega L i_{sq} + V_{cd} - V_{sd})$ and $V_q = (-\omega L i_{sd} + V_{cq} - V_{sq})$, therefore (1) can be rewritten as:

$$\frac{di_{sd}}{dt} = -\frac{R_t}{L_t} i_{sd} + \frac{V_d}{L_t} \quad (2a)$$

$$\frac{di_{sq}}{dt} = -\frac{R_t}{L_t} i_{sq} + \frac{V_q}{L_t} \quad (2b)$$

V_d and V_q are obtained from proportional and integral controllers (*PI*) as follows:

$$V_d = k_{pi}\left(i_{sd}^* - i_{sd}\right) + k_{ii}\int\left(i_{sd}^* - i_{sd}\right)dt \quad (3a)$$

$$V_q = k_{pi}\left(i_{sq}^* - i_{sq}\right) + k_{ii}\int\left(i_{sq}^* - i_{sq}\right)dt \quad (3b)$$

Where k_{pi} and k_{ii} are current controller gains, i_{sd} and i_{sd}^* is the converter desired and reference direct axis current, i_{sq} and i_{sq}^* are the converter desired and reference quadrature axis current. Replace the integral parts of the V_d and V_q by $z_1 = k_{ii}\int\left(i_{sd}^* - i_{sd}\right)dt$ and $z_2 = k_{ii}\int\left(i_{sq}^* - i_{sq}\right)dt$, then

$$V_d = k_{pi}\left(i_{sd}^* - i_{sd}\right) + z_1 \quad (4a)$$

$$V_q = k_{pi}\left(i_{sq}^* - i_{sq}\right) + z_2 \quad (4b)$$

Differentiate artificial variables equations with respect to the time variable; the following differential equations are obtained:

$$\frac{dz_1}{dt} = k_{ii}\left(i_{sd}^* - i_{sd}\right)$$

(5a)

$$\frac{dz_2}{dt} = k_{ii}\left(i_{sq}^* - i_{sq}\right)$$

(5b)

From the set of first-order differential equations (2) to (5), the following equations are obtained:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ Z_1 \\ i_{sq} \\ Z_2 \end{bmatrix} = \begin{bmatrix} \frac{-(R_t + k_{pi})}{L_t} & \frac{k_{ii}}{L_t} & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & \frac{-(R_t + k_{pi})}{L_t} & \frac{k_{ii}}{L_t} \\ 0 & 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} i_{sd} \\ Z_1 \\ i_{sq} \\ Z_2 \end{bmatrix} + \begin{bmatrix} \frac{k_{pi}}{L_t} & 0 \\ 1 & 0 \\ 0 & \frac{k_{pi}}{L_t} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} \quad (6)$$

Equation (6) indicates that the variable i_{sd} and i_{sq} are decoupled and the transfer function of the current controller is:

$$\frac{i_{sd}(s)}{i_{sd}^*(s)} = \frac{\frac{k_{pi}}{L_t}s + \frac{k_{ii}}{L_t}}{s^2 + \frac{(k_{pi} + R_t)}{L_t}s + \frac{k_{ii}}{L_t}}$$

(7)

The selection of the current controllers' gains can be accomplished using root-locus or frequency domain techniques [17]. The BESS uses AC network frequency and voltage as a control signals to respond to frequency variation and maintaining bus voltage. Using these signals the references are supplied to the inner controller using two additional outer loops designed as follow:

$$i_{sd}^* = k_{pf}(f^* - f) + k_{if}\int(f^* - f)dt \quad (8)$$

$$i_{sq}^* = k_{pac}(V_{ac}^* - V_{ac}) + k_{iac}\int(V_{ac}^* - V_{ac})dt$$

(9)

Where k_{pf} and k_{if} are frequency controller gains while where k_{pac} and k_{iac} are ac voltage controller gains, V_{ac}^* is the reference ac voltage and V_{ac} is the voltage at bus 2. Figure 2 summarizes the control system of the battery energy storage systems used in this paper. The dynamic response of the converter during power levelling is described by:

$$2H_c\frac{d\Delta\omega}{dt} = \Delta P_{dc} - \Delta P_L$$

(10)

where $\Delta\omega$ is frequency deviation, ΔP_{dc} is charged/or discharged power, ΔP_L is the load change, and H_c is the effective DC inertia constant, defined as [18]:

$$H_c = \frac{\frac{1}{2}CV_{dc}^2}{S_n}$$

(11)

Where C is the DC capacitor, V_{dc} is the DC voltage and S_n is the nominal power of the converter. The VSC inertia is in the range (10-40) ms with fast response compared to conventional machine which has large inertia. If two or more BESS is connected to the system, the contribution of each unit in order to stabilize the frequency is nearly proportion to their rating (S) which similar to that in synchronous machines having the same droops as shown in (12). Where H is converter inertia

$$\frac{\Delta P_1}{\Delta P_2} = \frac{H_2}{H_1} = \frac{S_1}{S_2}$$
(12)

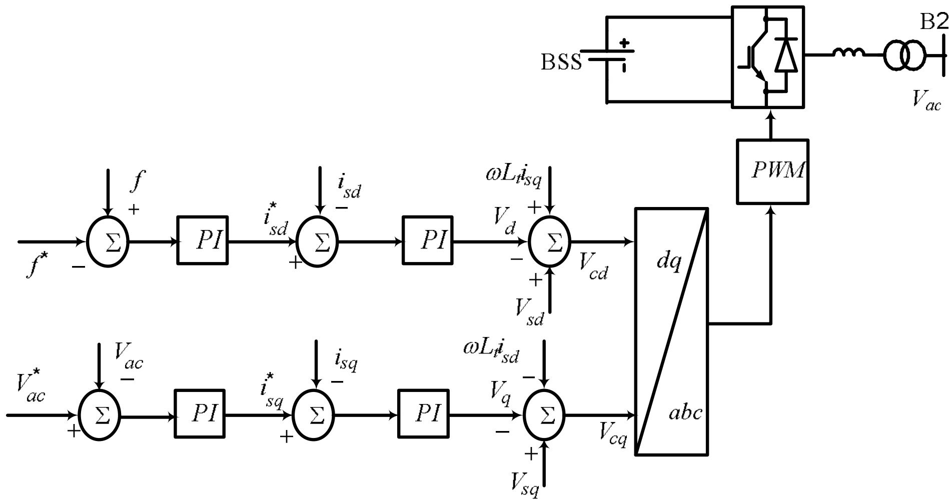


Figure 2: BSS control system block diagram

AC Voltage and Reactive Power Control:
Maintaining AC voltage at the wind farm network would be a great importance to power systems engineers. This is because AC voltage becomes sensitive to generation and load variations. Since wind farms always located remotely from load centers long transmission systems are required to accommodate the wind power into mainland. The inductive nature of the line and the wind generation variability may lead to the fluctuation in voltage profile at wind farm terminal. In this case BESS is used to maintain the voltage. The inherent reactive power capability of the voltage source converters allow them to operate in leading, unity or lagging power factor so that they can support the voltage profile at the point of common coupling by manipulating the reactive power exchange between the converter and the system. The active and reactive power exchange between converter VSC and B_2 is [19, 20]:

$$\vec{I}_{c1} = \frac{\vec{V}_1 - \vec{V}_{c1}}{jX_{t1}} = \frac{1}{X_{t1}}\left[V_1 e^{-\frac{1}{2}\pi j} - V_{c1} e^{j(\delta_{c1}-\frac{1}{2}\pi)}\right] \quad (13)$$

$$P_{c1} + jQ_{c1} = \vec{V}_1 \vec{I}^*_{c1} = \frac{V_1^2}{X_{t1}} e^{j\frac{1}{2}\pi} - \frac{V_1 V_{c1}}{X_{t1}} e^{j(\frac{1}{2}\pi - \delta_{c1})}$$
(14)

$$P_{c1} = \frac{V_1 V_{c1}}{X_{t1}} \sin \delta_{c1}$$
(15)

$$Q_{c1} = \frac{V_1^2}{X_{t1}} - \frac{V_1 V_{c1}}{X_{t1}} \cos \delta_{c1}$$
(16)

Where, I_{c1} is converter current, V_1 is system voltage at point of common coupling, V_{c1} is converter voltage, P_{c1} is converter active power, Q_{c1} is converter reactive power, and X_{t1} is equivalent reactance between the converter and system bus, δ_{c1} is the angle between V_1 and V_{c1}.
Phasor diagram in Figure 3 illustrates the four quadrant operation of BESS when interfaced using voltage source converter. It can be observed that the VSC capacitive reactive power capability is limited by the DC link voltage V_{dc}, as V_c in Figure 2 is related to DC link voltage by $V_c = \frac{1}{2} m V_{dc}$, where m is modulation index. Inductive

reactive power is limited switching devices current ratings as the converter tries to deliver the same active at reduced voltage as illustrated in Figure 3.

Figure 3: Phasor diagram depicts active andreactive power control of voltage source converter and their limits

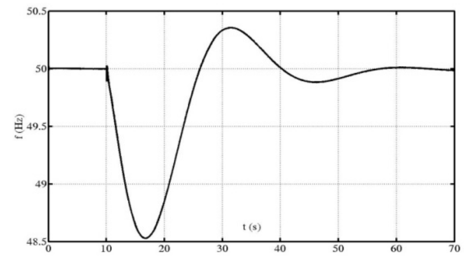
Simulation Results:

In order to demonstrate the effectiveness of the battery storage system to achieve the power levelling, frequency stabilization and voltage control at PCC in the system, two scenarios are investigated:

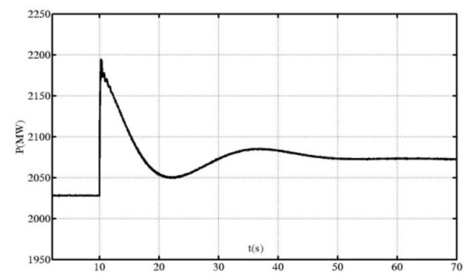
1. The first scenario considers change in load-demand.
2. The second considers increase in the wind farm output power.

Scenario I: System behaviour during load-demand change

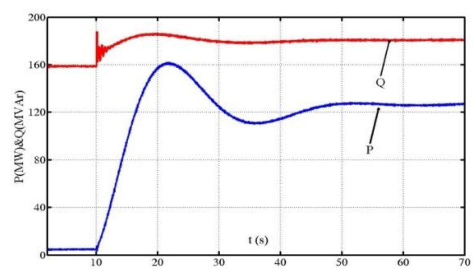
Electrical power system power mismatch may occur due to many reasons such as sudden loss of major load, outage of generation unit or transmission line. In this section BESS role and system dynamics stability when the system in Figure 1 is exposed to sudden load change initiate by suddenly connecting a load of S_{L2}= (180+j115) MVA to ac bus B_1 at time t=10s. This lead to significant active power mismatch between the generation and load demand and affect frequency stability as shown in Figure 4a. Figure 4a shows a significant decrease in AC network frequency with the introduction of load S_{L2} into bus B_1. As a result the BESS control system sense the frequency decrease and responded by supporting the ac network through injection appropriate amount of active power in order to stabilize network frequency to its nominal value (50Hz) as shown in Figure 4c. The BESS inject about 120MW in order to help in system stability while turbine-governor controller in the conventional power plant is activated and adjust generator output to cover the remaining power required to stabilize the frequency as shown in Figure 4b. It can be observed that the majority of the power for frequency stabilization comes from the BSS system due to the small inertia of the converter. Figure 4d shows that the voltage magnitude at the B_2 is maintained at 1.0 pu although the change in active power flow as the BESS adjusts its reactive power exchange with the wind farm main bus B_2 (see Figure 4c). It is obvious that BESS limit frequency variation caused by sudden power imbalance within specific time (20 to 30 s) [18].



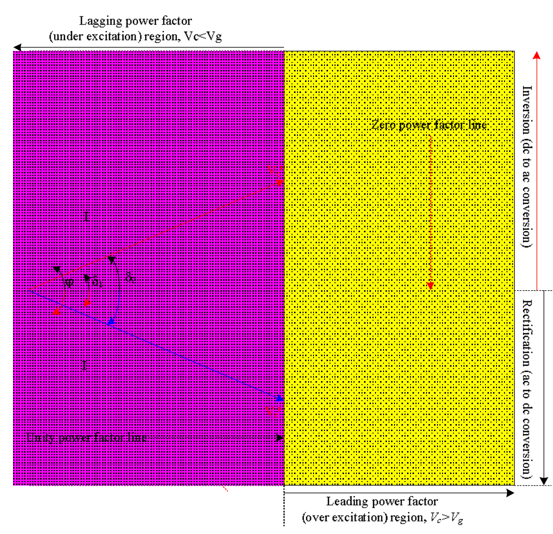
a. Network frequency



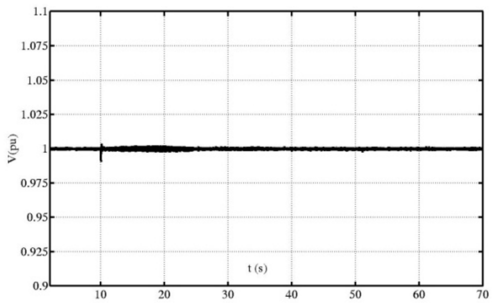
b. Synchronous generator active power



c. Battery storage system active



and reactive



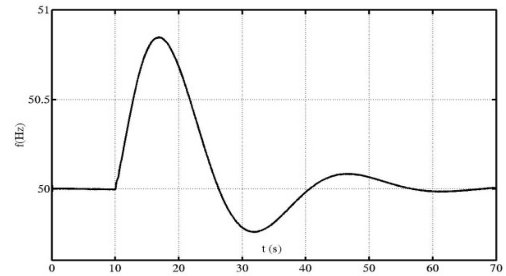
d.Wind farm terminal voltage

e.

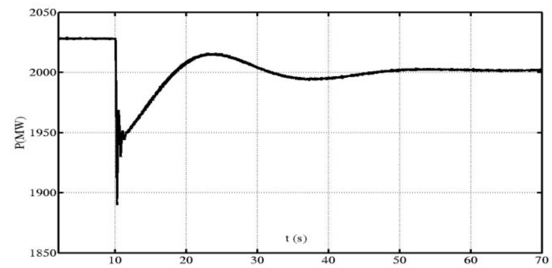
Figure 4: Waveforms demonstrating the stabilization role of BESS during large load increased

Scenario II: System behaviour during wind power increase

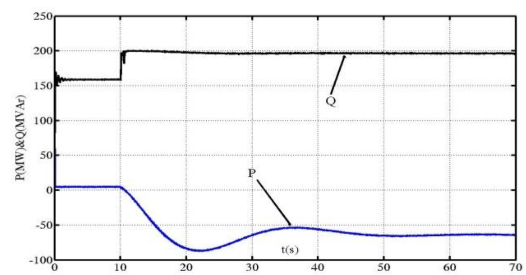
The potential benefits of installation of BESS in conjunction with wind power plants are to achieve the power balancing in the system during variation in wind power and to provide the required reactive power compensation for the older design of the wind farms based on fixed speed turbine [21]. This section assesses the feasibility of the BESS in stabilization of AC network, namely AC network frequency, voltage and minimization of active power mismatch following surge in wind farm power outputs due to large wind storm at offshore. Figure 5 show the results obtained when the wind farm increases its output power (see Figure 5d) due to sudden increase in wind speed from 11m/s to 14m/s. In this case the frequency is increase as shown in Figure 5a because the generation is greater than the demand and recover to nominal value after the responses from BESS and synchronous generator. The BESS is responded by absorbing the additional active power in the AC network that causes network frequency to increase by changing its status from discharging to charging and reversed its power flow direction as shown in Figure 5c. Also it can be seen that the synchronous generator adjusts its output power slowly to participate in frequency regulation as shown in Figure 5b. The BESS continue to provide the reactive power control to keep the voltage at wind farm by regulate the reactive power exchange with the system terminal as shown in Figure 5c. In both scenarios the BESS has prove its effectiveness to maintain system frequency and to act as slack bus units in conventional AC power systems, in addition provision of voltage support to the wind farm.



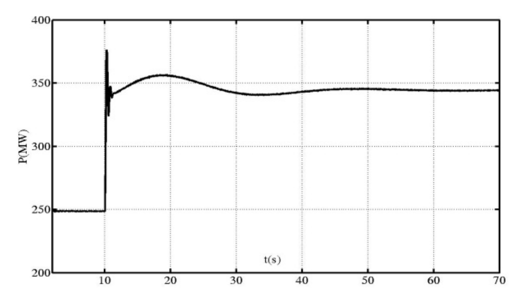
a. Network frequency



b. Synchronous generator power



c. Battery storage system active and reactive



d. Wind farm active power

Figure 5: Waveforms demonstrating the stabilization role of BESS as wind farm increases its out power

Conclusion:

This paper investigated the potential use of battery energy storage system (BESS) in relatively weak AC network with high penetration of wind power. It has been illustrated that this approach may enable maximum penetration of the wind power into AC networks without affecting the system power balance. Also the BESS system could be used to provide ancillary services to the AC network as conventional power plant but with much faster dynamic response.

References:

1. Acarnley, P.P.; Mecrow, B.C.; Burdess, J.S.; Fawcett, J.N.; Dickinson, P.G.; Kelly, J.G. "An integrated flywheel/machine energy store for road vehicles," in *New Topologies for Permanent Magnet Machines (Digest No: 1997/090), IEE Colloquium on*, 1997, pp. 9/1-9/6.

2. Giddani, *O.A;*Adam, G.P. ; Anaya-Lara, O. ; Burt, G. ;Lo,K.L. ,"Control strategies of VSC-HVDC transmission system for wind power integration to meet GB grid code requirements," in *Power Electronics Electrical Drives Automation and Motion (SPEEDAM), 2010 International Symposium on*, 2010, pp. 385-390.

3. Banzo, M; and Ramos, A;. "Stochastic Optimization Model for Electric Power SystemPlanning of Offshore Wind Farms a large offshore wind farm," *Power Systems, IEEE Transactions on,* vol. 26, Issue. 6 pp. 1338-1348,2011.

4. Nanahara, T; and Takimoto, A;. "A study on required reservoir size for pumped hydro storage," *Power Systems, IEEE Transactions on,* vol. 9, pp. 318-323, 1994.

5. Akagi, H,."Keynote speech - active filters and energy storage systems for power conditioning in japan," in *Power Electronics Systems and Applications, 2004. Proceedings. 2004 First International Conference on*, 2004, pp. 78-79.

6. D. Kottick, M. Balu, D. Edelstein,"Battery Energy Storage for frequency regulation in an Island Power," *IEEE Transctions in Energy Conversion*, *1993. vol. 8, Issue 3*, pp. 455-459.

7. C.-F. Lu, C.-C. Liu, C.-J. Wu,," Effect of battery energy storage system on load frequency control considering governor deadband and generation rate constraint" *IEEE Transctions in Energy Conversion*, *1995. vol. 10, Issue 3*, pp. 555-561.

8. S. K. Aditya-F. and D.Das," Battery energy storage for load frequency control of an interconnected power system " Electric Power Systems Research, *2001. vol. 58,* pp. 179-185.

9. Anaya-Lara, Olimpo; Hughes, Michael; Jenkins, Nicholas., "Minimum synchronous generation for stability of DFIGURE based wind farms," in *Electricity Distribution, 2005. CIRED 2005. 18th International Conference and Exhibition on*, 2005, pp. 1-5.

10. Anaya-Lara, O.; Hughes, F.M.; Jenkins, N.; Strbac, G..,"Provision of a synchronising power characteristic on DFIGURE-based wind farms," *Generation, Transmission & Distribution, IET,* vol. 1, pp. 162-169, 2007.

11. Lemofouet, S; and Rufer, A;."A Hybrid Energy Storage System Based on Compressed Air and Supercapacitors With Maximum Efficiency Point Tracking (MEPT)," *Industrial Electronics, IEEE Transactions on,* vol. 53, pp. 1105-1115, 2006.

12. Derk, J.S,."Compressed Air Energy Storage in an Electricity System With Significant Wind Power Generation," *Energy Conversion, IEEE Transactions on,* vol. 22, pp. 95-102, 2007.

13. Joseph, A; and Shahidehpour, M;."Battery storage systems in electric power systems," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 8 pp.

14. K. C. Divya. and J. Qstergaard," Battery energy storage technology for power system " Electric Power Systems Research, *2009. vol. 79,* pp. 511-520.

15. L. Xu, *et al.*, "VSC transmission operating under unbalanced AC conditions - analysis and control design," *Power Delivery, IEEE Transactions on,* vol. 20, pp. 427-434, 2005.

16. Yazdani, A; and Iravani, R,."Dynamic model and control of the NPC-based back-

toback HVDC system," *Power Delivery, IEEE Transactions on,* vol. 21, pp. 414-424,2006.

17. Douangsyla, S.; Indarack, P.; Kanthee, A.; Kando, M.; Kittiratsatcha, S.; Kinnares, V. "Modeling for PWM voltage source converter controlled power transfer," in *Communications and Information Technology, 2004. ISCIT 2004. IEEE International Symposium on*, 2004, pp. 875-878 vol.2.

18. Cuiqing Du; Bollen, M.H.J.; Agneholm, E.; Sannino, A. "A New Control Strategy of a VSC HVDC System for High-Quality Supply of Industrial Plants," *Power Delivery, IEEE Transactions on,* vol. 22, pp. 2386-2394, 2007.

19. Bahrman, M.P; and Johnson, B.K,." The ABCs of HVDC Electricity System transmission technologies," *Power and Energy Magazine, IEEE,* vol. 5, pp. 32-44, 2007.

20. Cetin, A; and Ermis, M,."VSC-Based D-STATCOM With Selective Harmonic Elimination," *Industry Applications, IEEE Transactions on,* vol. 45, pp. 1000-1015,2009.

21. I. M. d. Alegrı*; Andreu, J;* Martín; J.L; Ibañez, P; Villate, J.L; Camblong, H, "Connection requirements for wind farms: A survey on technical requirements and regulation," *Renewable and Sustainable Energy Reviews Volume 11, Issue 8, October 2007, Pages 1858-1872*.

22. S. K. Aditya-F. and D.Das," Dynamic model of of a lead acid Battery e for use in a domestic load fuel cell system " Journal Power Sources, *2006. vol. 161,* pp. 1400-1411.

23. O. Termblay; L-A. Dessaint; and and A-Illah Dekkiche," A generic Batterry Model For the Dynamic Simulation of Hybrid Electric Vehicles " IEEE Vehicles Power and propulsion Confernce, *2007.* pp. 284-287.

Appendix A: Battery Storage System Model

Mathematical model of battery energy storage system battery models represent the BESS during charging or discharging conditions. There are numerous factors that affect a battery's operation including discharge rate, charge rate, battery age, battery type, and temperature. The most common used dynamics models are:

1. Linear or simplified model

The most simple and commonly used model of a battery consists of a constant resistance R_0 in series with an ideal voltage source E_0 as shown in Figure A1, where V_o is battery terminal voltage [22]. Since battery internal resistance is varies with temperature and depend on battery state of charge (SOC) this model is not suitable in modelling the battery because it does not take into account the varying characteristic of the internal resistance of the battery with respect to SOC and temperature changes. Such modal only applies in some circuit calculation or simulation where the energy from E_o is assumed to be unlimited.

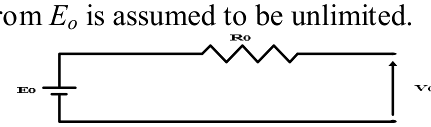


Figure A1: battery simplified model

2. Thevenin Model

The second most common used model is the Thevenin battery model which includes an ideal no load battery voltage *(E_o)*, internal resistance *(R)*, capacitance *(C_0)* and over-voltage resistance (R_0) as shown in Figure A2 [22, 23]. The component C_0 represents the battery capacity where the battery mostly delivers or stores energy and behaves as a large capacitor. Also the model assumed the elements are all constant although all the values are function of battery conditions.

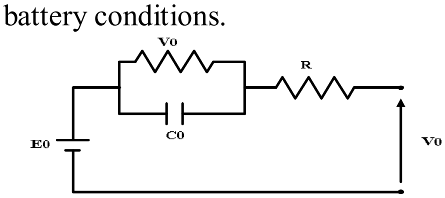


Figure A2: battery Thevenin model

3. Modified Model

The simplified model is modified to take battery state in consideration by replace the constant voltage source with controllable voltage source which change battery no load voltage according to state of charge as shown in Figure A3. The value of E_0 is changed depend on battery current, battery extracted capacity and low frequency current dynamic. (*Sel*) represent the battery status mode which are charge or discharge.

The controllable voltage source voltage is calculated as follow [23]:

During charging conditions

$$f_1 = E_0 - K.\frac{Q}{Q - i(t)}.i_d - K.\frac{Q}{Q - i(t)}.i_t + A.\exp(B.i(t))$$

(A-1)

While it's as in (A-2) during discharging conditions

$$f_2 = E_0 - K.\frac{Q}{i(t) + 0.1Q}.i_d - K.\frac{Q}{Q - i(t)}.i_t + A.\exp(B.i(t))$$

(A-2)

Where,

E_0 is controllable voltage source voltage

Q maximum batter capacity

A exponential voltage

B exponential capacity

K polarization constant

i_t extracted capacity

i_d low frequency current dynamic

sel represent battery mode (its 0 during discharge and 1 during charging mode)

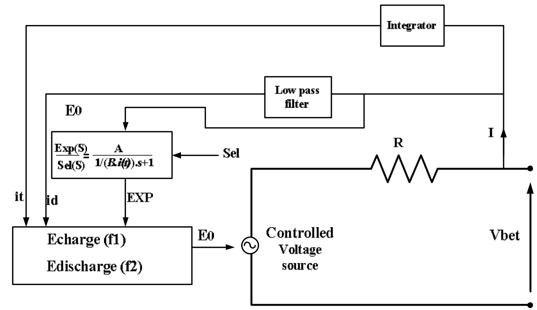


Figure A3: battery Modified mode