Distributed Storages Systems for Frequency Stabilization in the Future Power Systems

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Abstract

This paper investigates the frequency stabilization of highly-distributed future ac networks with high penetration of wind generation and energy storage systems. The investigation focuses on frequency stabilization during unintended split of the ac network into small clusters following large network disturbances, and during power unbalance due to the variability of the wind farms output, which are operated with a maximum power tracking scheme. Such frequency stabilization mechanism will be crucial in any practical realization of future micro and smart grids where the priority is to prevent loss of electricity supply following large permanent network faults. The validity of the presented concepts is demonstrated using MATLAB and SIMULINK simulations.

Keywords

Battery Energy Storage System; Frequency Stability; Renewable Energy Recourse; Smart Grid and VSC

Introduction

At present, in Europe there is a general agreement among governments, environmental organizations and power industry to replace the ageing power generation facilities that use fossil fuels and nuclear by new power plants with that based on sustainable renewable resources such as wind and solar, leading to rethinking within the power industry which has resulted in changes in the connection philosophy of the electricity network from centralized to decentralized systems. The concept of decentralized electrical power systems is well suited for accommodation of large number of renewable power plants distributed over a wide area without significantly compromising the reliability and security of the energy supply. The smart grids concept has been developed to facilitate the implementation decentralized power systems, as they can be connected together to operate as a large power system, or split into viable small, safe and secure ac networks capable of maintaining their active and reactive power balance and frequency stability. Such concept may reduce transmission losses and risk of system blackout following large network disturbances (S. Galli, A. Scaglione, Z.Wang, 2011; K. Moslehi and R. Kumar,2010). As the current concepts of the smart grids are developed around synchronous ac network, increased extension of installations of large renewable power plants may require intensive use of flexible ac transmission devices (FACTS), and energy storage systems. This is to facilitate power control and balance, improve utilization of the ac lines; address power quality issues, including voltage stability problems; and public interest regarding environmental issues. Successful transition from current centralized systems to fully decentralized networks may also require large investments in infrastructure.

In the last 50 years, a lot of researches have been conducted in energy storage systems. This resulted in introduction of several storage technologies into power systems to provide ancillary services. However, more research is needed in scalability and efficiency improvement of storage energy systems. Some of the energy storage systems are summarizes as follow (A. Joseph and M. Shahidehpour,2006; B. P. Roberts and C. Sandberg,2011; P.F .Ribeiro, B.K Johnson, M.L.Crow, A. Arsoy, and Y. Liu, 2001):

Pumped hydro: represents the dominant and oldest storage technologyand always located far away from the load centre where the water is available. It can use energy to provide load leveling and other ancillaries such as frequency support. The main disadvantage of this option is the low time response.

Compressed air: stores the energy using a process where air is compressed during times of excess energy and the air is run through a turbine when power is needed. It has received significant attention recently as a means to address the intermittence problems with wind power. However, applications of such storage system are limited due to increased losses and high space requirements to store the compressed air.

Flywheel: stores the excessive energy as kinetic energy in rotating mass during off-peak and released when needed. Unlike batteries, it provides sustainable technology solutions that neither use hazardous materials for production, nor create them during operation. It holds relative good storage capacity, fast response, long lifetime and required minimum maintenance.

Super capacitors: the capacitor is attractive due to its long life cycle and rapid charging using simple methods. The main limitations are low energy storage capacity; cells with low voltages, therefore series connections are needed to obtain higher voltages; and high self discharge.

Batteries: there are many types of battery energy storage systems. The Lithium-ion (Li-ion) battery is the most important type that offers high energy density compared to other systems, and has the potential to become the dominant energy storage means for electric/hybrid vehicles, and medium-scale energy storage that may facilitate increased penetration of renewable energy generations into ac power systems. However, they require ac/dc converter in order to operate in synchronous power systems.

This paper focuses on the power balancing and the frequency stabilization of future ac networks with high penetration of renewable power and distributed energy storage systems in order to enable operation as one large ac grid or safe split into secure small clusters of ac networks following large permanent ac network disturbances. Therefore, for illustration purposes, this paper considers a generic ac network with high penetration of renewable power generation and distributed storage systems to demonstrate ac network frequency stabilization and safe split of ac network.

Smart Grids Concept

The increase in energy consumptions due to the energy-intensive lifestyle of modern societies requires high-quality and guaranteed power supply from sustainable resources with minimum environmental impact. Therefore, most of the existing conventional power plants based on fossil fuels are expected to be forced out of services due to new environmental standards currently established. In conventional power system, the power flow has one direction from the supply to the demand centre, the system abnormal condition is propagate into whole entire system and the power leveling is achieved via turbine-governor of generators. One of the greatest challenges of power system highly populated with distributed generations is that the variability nature of the wind and photovoltaic (A. Molderink, V. Bakker, M.G.C. Bosman, J.L. Hurink, and G.J.M. Smit, 2010). This challenge can be addressed through intensive use of power electronics technologies in the context of smart grids. These technologies must be able to achieve the power balancing in the event of the fluctuation in renewable distributed plants, and provide additional functionalities such as reactive power compensation, frequency stabilization and synthetic inertia. Installation of distributed renewable power generation and smart distributed storage systems that use power electronics converters convert the conventional power system into new decentralized (sometime it known as smart grid or future power system), inelegant and self healing power system. In general, smart grids must inherent the following features ((A. Molderink, V. Bakker, M.G.C. Bosman, J.L. Hurink, and G.J.M. Smit, 2010; G. T. Heydt, 2010; Z. Ruihua, D. Yumei and L. Yuhong,2010)

- Clean and green, and highly populated with small to large-scale distributed renewable power generations.
- Installation of FACTs device to enhance transmission lines
- Installation of energy power storages in order to achieve power leveling.
- High speed and reliable digital communication system to achieve monitoring and control.
- Self-healing from network disturbances such faults.
- Reliable and safety.
- Flexibility: expandable and must be able to operate in grid and islanding modes.
- Highly dependent on flexible ac transmission systems (FACTS) devices and storage systems to provide power quality for 21st century needs.

Battery Energy Storage System

Battery energy storage system (BESS) is considered in this paper because it has a potential to become a dominant energy storage means for electric vehicles, grid access for large wind farms and provision of ancillaries for large ac power systems. The use of BESS with renewable plants may allow them to behavior as virtual power plant capable to provide all the functionalities of conventional power plant, but much faster than conventional power plants based on synchronous machines. The BESS is normally interfaced to grid using bi-directional power flow converters that utilize dc link capacitors to decouple it from additional stresses during ac networks disturbances.

BESS achieves power leveling 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 unique features of the energy storage systems interfaced using voltage source converter are that it can provide frequency support and active power balancing and leveling when embedded in ac network, while HVDC transmission systems cannot provide these features when embedded in ac network (not connecting two isolated networks). In this paper, the power electronic converter used for interfacing of BESS is configured to act as STATCOM in order to regulate AC voltage in addition to stabilizing the system frequency, and to inhibiting 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 (F. Delea and J. Casazza,2010; L. Xu, B.R. Anderson, and P. Cartwright, 2005). The mathematical model of battery energy storage system is presented in Appendix A.

In this paper, converters BESS is controlled using carrier-based sinusoidal pulse-width modulation (SPWM), with 2 kHz switching frequency. The differential equation describing the VSC ac side dynamics is (L. Xu. , B.RAnderson, and P.Cartwright, 2005; D. Cuiqing, E. Agneholm, and G. Olsson, 2008; A. Yazdani and R. Iravani, 2006):

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

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

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

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

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

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

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

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

Where k_{pi} and k_{ii} are current controller gains, i_{sd} and i_{sd}^* are 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 artificial variables $z_1 = k_{ii}\int\left(i_{sd}^* - i_{sd}\right)dt$ and $z_2 = k_{ii}\int\left(i_{sq}^* - i_{sq}\right)dt$, then

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

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

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

$$\frac{dz_1}{dt} = k_{ii}\left(i_{sd}^* - i_{sd}\right) \qquad (5a)$$

$$\frac{dz_2}{dt} = k_{ii}\left(i_{sq}^* - i_{sq}\right) \qquad (5b)$$

The variable i_{sd} and i_{sq} are decoupled and the transfer function of the current controller is:

$$\frac{i_{sd(s)}}{i_{sd}^*(s)} = \frac{\dfrac{k_{pi}}{L_t}s + \dfrac{k_{ii}}{L_t}}{s^2 + \dfrac{\left(k_{pi} + R_t\right)}{L_t}s + \dfrac{k_{ii}}{L_t}} \qquad (6)$$

The selection of the current controllers' gains can be accomplished using root-locus or frequency domain techniques as: $k_{pi} = 2\zeta\omega_n L_t - R_t$ and $k_{ii} = \omega_n^2 L_t$ (P. Cominos and N. Munro,2002).

The references are supplied to the inner controller using two additional outer loop designed as follow:

$$i_{sd}^* = k_{pf}\,(f^* - f) + k_{if}\int(f^* - f)dt \qquad (7)$$

$$i_{sq}^* = k_{pac}(V_{ac}^* - V_{ac}) + k_{iac}\int(V_{ac}^* - V_{ac})dt \qquad (8)$$

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.

To facilitate the design of the frequency controller, it is assumed that the ac network has an equivalent inertia constant of H_2, and then the swing equation for the ac side can be expressed in terms of the ac network frequency as follow:

$$\frac{2H_2}{\omega_0} \times \frac{d\omega}{dt} = \frac{2H_2}{f_0} \times \frac{df}{dt} = \overline{\Delta P} \qquad (9)$$

$$\Delta P = k_{pf}\,(f^* - f) + Z_f \qquad (10)$$

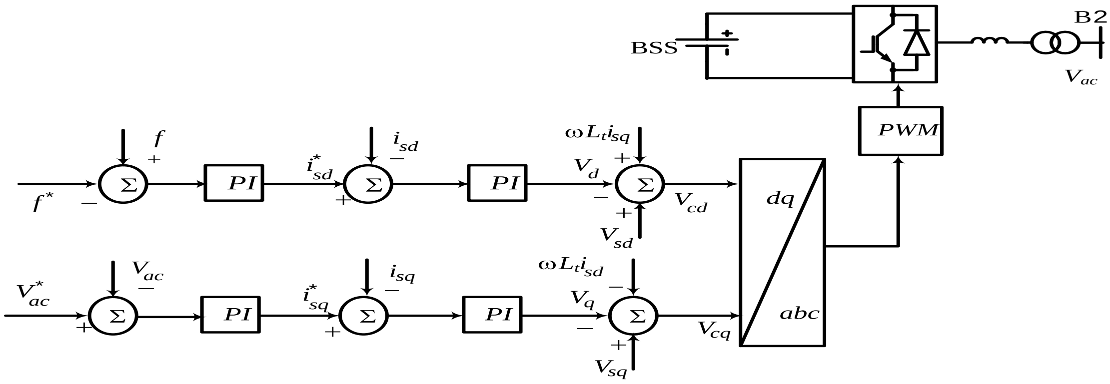


FIG. 1 BESS CONTROL SYSTEM BLOCK DIAGRAM

After algebraic manipulation of (7), (9) and (10), the following differential equations are obtained:

$$\frac{df}{dt} = \frac{f_0}{2H_2}\left[k_{pf}(f^* - f) + Z_f\right] \tag{11}$$

$$\frac{dZ_f}{dt} = k_{if}(f^* - f) \tag{12}$$

After Laplace manipulation of (11) and (12), the following transfer function is obtained:

$$\frac{f(s)}{f^*(s)} = \frac{f_0}{2H} \times \frac{k_{pf}s + k_{if}}{s^2 + \frac{k_{pf}f_0}{2H}s + \frac{k_{if}f_0}{2H}} \tag{13}$$

Using the same procedure adopted to select the current controller gains, the frequency controller gains are obtained as follow: $k_{pf} = \frac{4\zeta\omega_n H}{f_0}$ and $k_{if} = \frac{2\omega_n^2 H}{f_0}$

Fig. 1 summarizes the control system of the battery energy storage systems used in this paper.

The dynamic response of the BESS during the power leveling is

$$\frac{d\Delta\omega}{dt} = \frac{\omega_0}{2H_c}\left(\Delta P_{dc} - \Delta P_L\right) \tag{14}$$

Where $\Delta\omega$ is the frequency deviation, ΔP_{dc} is the change on the dc transmitted power, ΔP_L is the load change, and H_c is the effective dc inertia constant, which defined as (D. Cuiqing, E. Agneholm, and G. Olsson , 2008):

$$H_c = \frac{\textit{Total ac system inertia}}{\textit{MW}\ \text{rating of the dc system}} \tag{15}$$

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 similar to that in synchronous machines having the same droops as shown in (16)

$$\frac{\Delta P_1}{\Delta P_2} = \frac{H_2}{H_1} = \frac{S_1}{S_2} \tag{16}$$

AC Voltage and Frequency Control

As the world is moving toward decentralized power systems with distributed renewable power generations, maintaining ac voltage and frequency in future power system would be a great importance to power systems engineers. This is because ac voltage and frequency may become sensitive to load variations as power generation will be located remotely from load centers, and may require long transmission systems. The inductive nature of the line, sharp peak demand and the renewable generation variability may lead to the fluctuation in voltage profile of the ac transmission lines and frequency. BESS can be used to assist the future power system in maintaining its voltage profile and frequency. In the worse cases, it can be used to facilitate safe transitions from grid mode to islanding mode and vice versa. 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 (PCC). Four quadrant capabilities of the BESS interfaced with VSC as investigated in this paper may aid active power balance in the ac network, hence maintaining virtually constant network frequency. The active and reactive power of BESS exchange with the ac network at the point of common coupling can be defined as follow (M. P. Bahrman and B. K. Johnson, 2003):

The active and reactive power exchange between converter VSC_1 and B_{11} is:

$$\vec{I}_{c1} = \frac{\vec{V}_1 - \vec{V}_{c1}}{jX_{t1}} = \frac{1}{X_{t1}}\left[V_1 e^{-\frac{1}{2}\pi j} - V_{c1}e^{j(\delta_{c1} - \frac{1}{2}\pi)}\right] \tag{18}$$

$$P_{c1} + jQ_{c1} = \vec{V}_1\vec{I}^*_{c1} = \frac{V_1^2}{X_{t1}}e^{j\frac{1}{2}\pi} - \frac{V_1V_{c1}}{X_{t1}}e^{j(\frac{1}{2}\pi - \delta_{c1})} \tag{19}$$

$$P_{c1} = -\frac{V_1 V_{c1}}{X_{t1}} \sin \delta_{c1} \qquad (20)$$

$$Q_{c1} = \frac{V_1^2}{X_{t1}} - \frac{V_1 V_{c1}}{X_{t1}} \cos \delta_{c1} \qquad (21)$$

Phasor diagram in Fig. 2 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 Fig. 2 is related to dc link voltage by $V_c = \frac{1}{2} m V_{dc}$, where m is modulation index. Inductive reactive power exchange is limited due to converter devices current ratings as illustrated in Fig. 2.

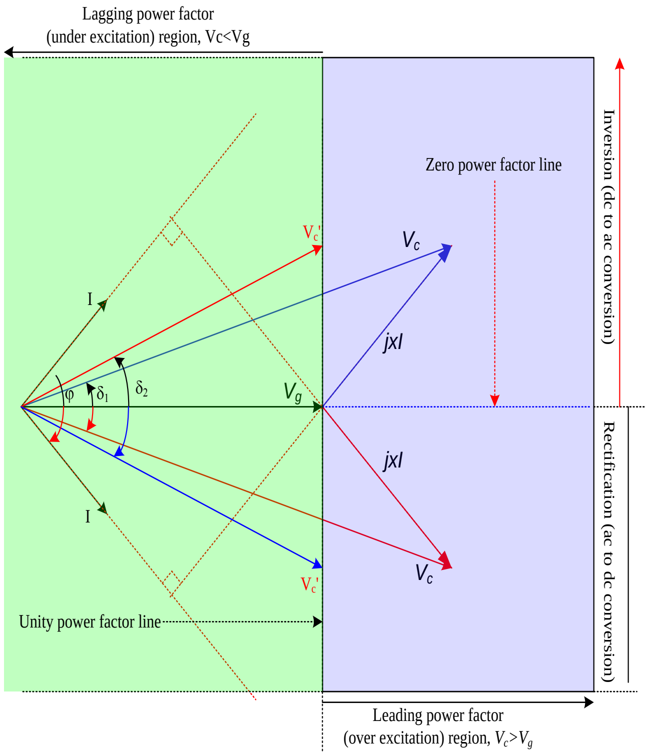


FIG. 2 PHASOR DIAGRAM DEPICTS ACTIVE AND REACTIVE POWER CONTROL OF VOLTAGE SOURCE CONVERTER AND THEIR LIMITS

Test System Lay-out

The test network in Fig. 3 comprises three independent ac networks, connected together to form a large interconnected power systems in line with the concept of smart grid. Networks 1 and 2 are identical and each of them includes 2400MVA conventional generation based on synchronous machine, 500MVA wind farm and 400MVA battery energy storage system connected to the network through voltage source converters. Network 3 includes only a 1000MVA synchronous generator (SG_3) connected to a large local load shown in Fig. 3. The three networks are connected together using ac transmission lines (TL_3 and TL_4) and circuit breakers (CB1, CB_2 and CB_3). The static loads are distributed across the network as shown in Fig. 3. The ac circuit breakers are used to split the ac networks into small clusters to facilitate the necessary scenarios which will be considered in this paper.

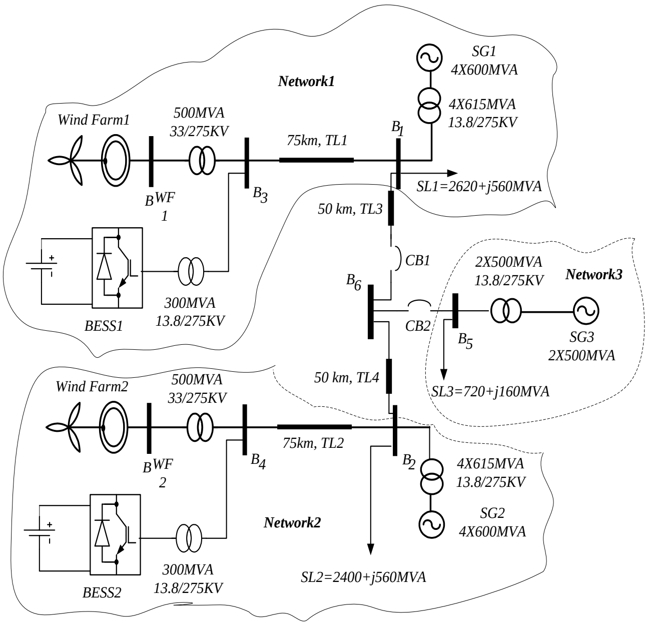


FIG. 3 TEST SYSTEM LAY-OUT

Simulation Results

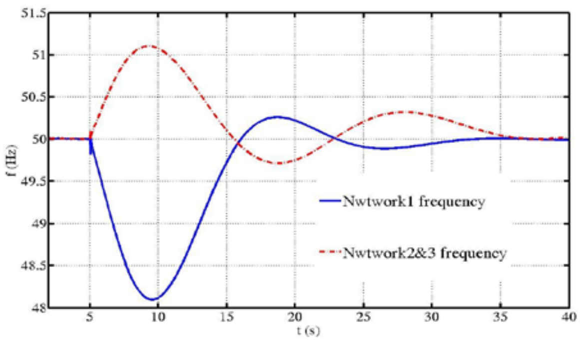
In interconnected power systems, the active power balance is strongly coupled to the frequency. Any mismatch between the generation and the demand may cause system frequency to change, depending on the net accelerating power experience by generators (A. Yakout, *O.Anaya.Lara, G.Burt,2009;* S. R. Pulikanti and V. G. Agelidis,2011*)*. The power mismatch occurs for several reasons such as:

1. Sudden change in injected wind power into system due to wind speed variations.
2. Losses of major loads or generation unit due to split of the interconnected system into small clusters.

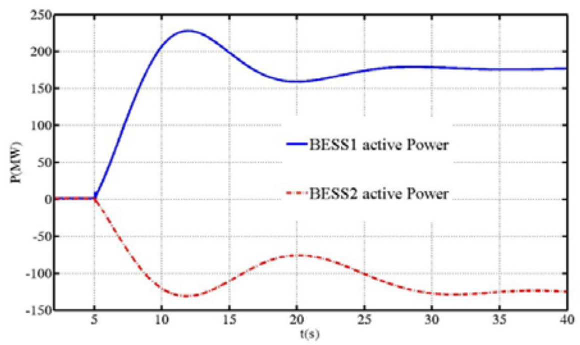
This section demonstrates the use of BESS for frequency stabilization of future ac networks during wind power variations and split of the system into small clusters. To assess the viability of such energy storage systems in maintain network frequency, active power balance, provision voltage support to the ac network facilitate increased wind power penetration, and the test network in Fig. 3 simulation under the following scenarios:

Scenario I: Network Islanding (Each Island Has BESS)

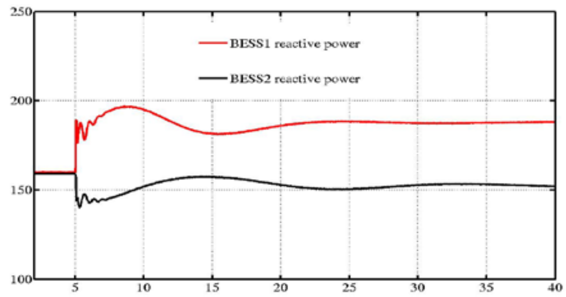
The objective of this scenario is to investigate the advantages of BESS installed with small islands during sudden split in future power system. This scenario is demonstrated by splitting the test network in Fig. 3 into small clusters by opening ac circuit breakers CB1 and CB2 (each island has BESS). First, the network split is initiated by opening the ac circuit breaker CB_1 at t=5s, resulting in two independent islands, both including active generation and BESS. It can be observed that both islands are able to recover their active power balance and nominal frequency after experiencing short-transient frequency instability due to active power mismatch created by the network split. In addition, it can be noticed that opening of circuit breaker CB1 causes ac network 1 to suffer from temporary under-frequency and ac network 2 and 3 from over-frequency as illustrated in Fig. 4a. Fig. 4b shows that BESS 1 and 2 adjust their power exchange with the ac networks to maintain the correct power balance. The synchronous generators also respond by adjusting their output power to contribute to the frequency stabilization of the ac network, but slowly due to their large mechanical inertias (Fig. 4e). It can be observed in both islands that the frequency recovers after the split within acceptable limits according to the Great Britain (GB) Grid Code (A. Yakout, *O.Anaya.Lara, G.Burt,2009*). Fig. 4c shows the reactive power exchange of BESS 1 and 2 with buses B_3 and B_4 in order to keep the voltages at these buses at 1.0pu as shown in Fig. 4d.



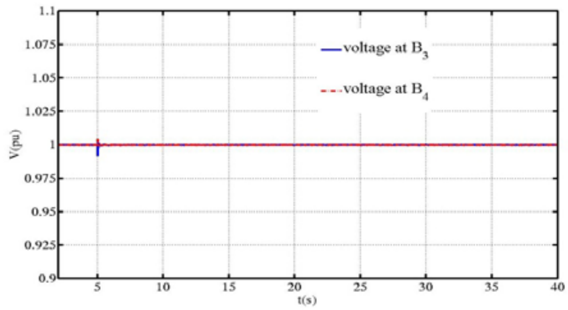
(a) Islands frequencies



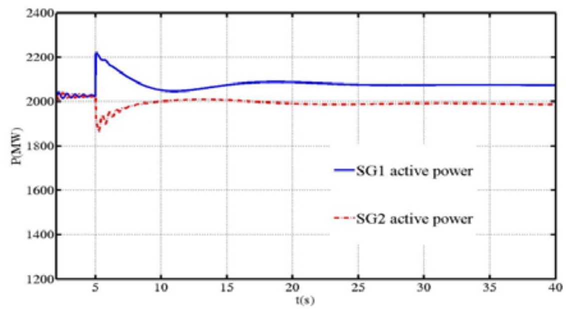
(b) Active power BESS 1 and 2 exchange with buses B_3 and B_4



(c) Active power BESS 1 and 2 exchange with buses B_3 and B_4



(d) Voltage magnitudes at ac buses B_3 and B^4

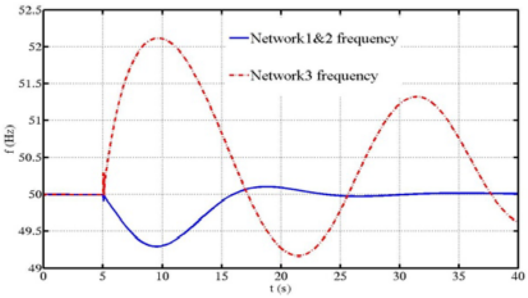


(e) Active power response of synchronous generators 1 and 2

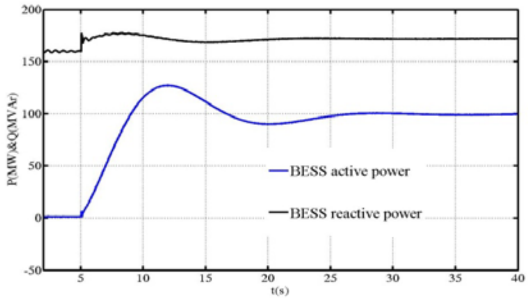
FIG. 4 KEY WAVEFORMS DEMONSTRATING FREQUENCY STABILIZATION OF THE TEST SYSTEM AFTER THE SPLIT INTO TWO INDEPENDENT ISLANDS BY OPENING CB_1

Scenario II: Network Islanding (There Island without BESS)

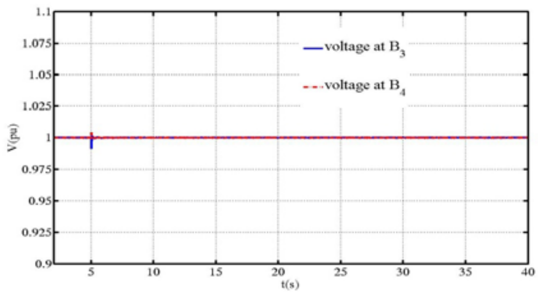
This section compare the response of small island with/ and without BESS during system splitting, and the investigation is initiated by opening CB_2 while CB_1 remains closed. When CB_2 is open at t=5 s, the system is split into two small islands (network1 and network2), and (network3). The island that includes network 1 and 2 has active generations and two BESSs. Whilst island 2 includes network 3 with active generation but no BESS. It can be observed that the ac island 2 experiences frequency instability for a longer period compared to island 1 that contains energy storage systems as shown in Fig. 4a. This figure shows that the BESSs have contributed significantly to the improvement in frequency response of the ac networks 1 and 2 due to their fast dynamic response. In Fig.4a network3 frequency has shown high overshoot and took long time to recover compared to island 1. Fig. 4b shows that both battery storage systems 1 and 2 inject 200 MW (100 MW each) in order to stabilize the network frequency. The synchronous generators 1 and 2 adjust their output power to contribute to frequency stabilization of the network 1 and 2 in conjunction with BESS (see Fig. 4d).



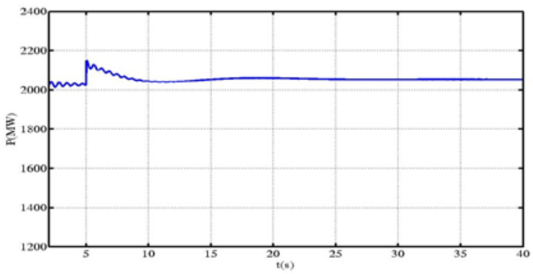
a) Islands frequency



b) Active power BESS 1 and 2 exchange with ac buses B_3 and B_4



c) Voltage magnitude at ac buses B_3 and B_4



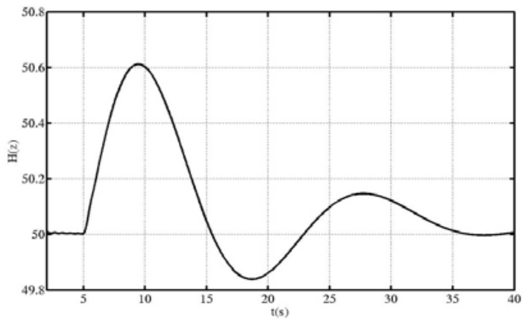
d) Active power response of synchronous generators 1 and 2

FIG. 5 KEY WAVEFORMS DEMONSTRATING FREQUENCY STABILIZATION AFTER OPENING OF CIRCUIT BREAKER CB_2

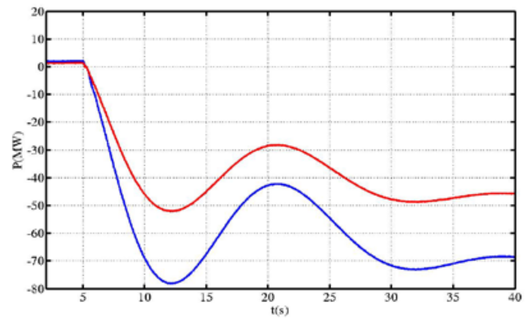
Scenario III: Power Balance during Wind Power Variations

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 [18]. This section assesses the feasibility of the BESS in stabilization of ac network, namely ac network frequency and voltage and minimization of active power mismatch following surge in wind farm power outputs due to large wind storm at offshore. In this scenario, the rating of BESS2 is 200 MVA in order to investigate the power sharing of each BESS required to stabilize the frequency. This scenario is tested by increasing the wind speed suddenly from 11 m/s to 14 m/s at t=5 s. As shown in Fig. 5c, the wind power generation is increased by 110 MW due to step change wind speed. It can be observed from Fig. 5a that the network frequency is increased and then recovers to its nominal frequency of 50Hz as BESSs responded by adjusting their active power exchange with busses B_3 and B_4 (as shown in Fig. 6b) together with the conventional generators (as shown in Fig. 6d) in order to stabilize ac network frequency and voltage magnitude at (B_3 and B_4).

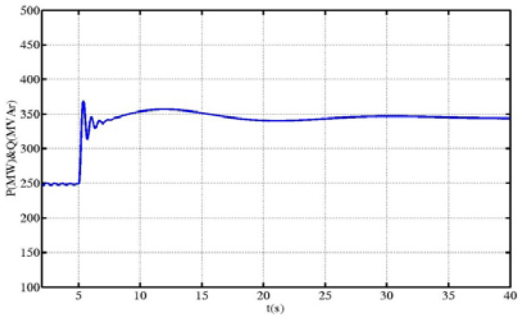
It can be noticed that the load sharing between the BESS 1 and 2 is approximately based on their power ratings. This is conformed in Fig. 6b as the BESS 1 and 2 power exchange with B_3 and B_4 that are 74 MW and 49 MW, which is nearly equal to the ratio of BESSs rating (300/200).



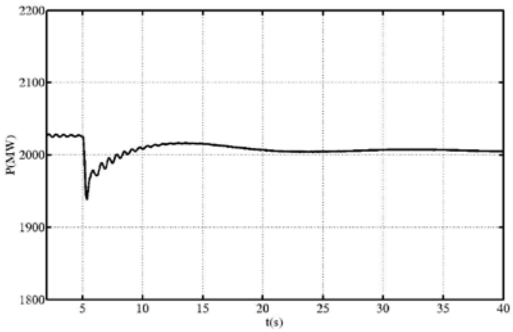
(a) Interconnected network frequency



(b) Active power BESS 1& 2 exchange with busses B_3 and B_4



(c) Offshore wind farms active power



(d) Active power response of synchronous generators 1&2

FIG. 6 KEY RESULTS EXPLAINING THE NETWORK BEHAVIOR WHEN THE WIND POWER GENERATION IS INCREASED

Conclusions

This paper has investigated the frequency stabilization of future power systems with increased penetration of renewable power using distributed energy storage systems, and also has highlighted the potential benefits of decentralized power systems in terms of security of supply, flexibility of dispatch, low transmission losses, prevention of system blackout and increased accommodation of renewable power. The technical feasibility of BESS for ac network frequency and voltage stabilization during several contingencies such as transition from grid-connected mode to islanding, loss of major generation, and accommodation of unpredicted change in power output of renewable power plants is demonstrated.

REFERENCES

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

A. Molderink, Bakker, M.G.C. Bosman, J.L. Hurink, and G.J.M. Smit, "Management and Control of Domestic Smart Grid Technology," *Smart Grid, IEEE Transactions on*, vol. 1, pp. 109-119, 2010.

A. Yakout, O.Anaya.Lara, G.Burt,"Improving the transient frequency response of unintentional islands via local optimal controllers," in *Advances in Power System Control, Operation and Management (APSCOM 2009), 8th International Conference on*, 2009, pp. 1-6.

A. Yazdani and R. Iravani, "Dynamic model and control of the NPC-based back-to-back HVDC system," *Power Delivery, IEEE Transactions on*, vol. 21, pp. 414-424, 2006.

B. P. Roberts and C. Sandberg, "The Role of Energy Storage in Development of Smart Grids," *Proceedings of the IEEE*, vol. 99, pp. 1139-1144, 2011.

D. Cuiqing, E. Agneholm, and G. Olsson, "USE of VSC-HVDC for Industrial Systems Having Onsite Generation With Frequency Control," Power Delivery, IEEE Transactions on, vol. 23, pp. 2233-2240, 2008

F. Delea and J. Casazza, *An Overview of the Technology, the Marketplace, and Government Regulation*, 2010.

G. T. Heydt, "The Next Generation of Power Distribution Systems," *Smart Grid, IEEE Transactions on*, vol. 1, pp. 225-235, 2010.

K. Moslehi and R. Kumar, "Smart Grid- a reliability perspective," in *Innovative Smart Grid Technologies (ISGT), 2010*, 2010, pp. 1-8.

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

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

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

P. Cominos and N. Munro, "PID controllers: recent tuning methods and design to specification," *Control Theory and Applications, IEE Proceedings -*, vol. 149, pp. 46-53, 2002.

R P.F .Ribeiro, B.K Johnson, M.L.Crow, A. Arsoy, and Y. Liu, "Energy Storage Systems for Advanced Applications", proceeding of IEEE, Vpl:89, Issue: 12, Page(s): 1744-1756, Dec 2001.

S. Galli, A. Scaglione, Z.Wang "For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid," *Proceedings of the IEEE*, vol. 99, pp. 998-1027, 2011.

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

S. R. Pulikanti and V. G. Agelidis, "Hybrid Flying-Capacitor-Based Active-Neutral-Point-Clamped Five-Level Converter Operated With SHE-PWM," *Industrial Electronics, IEEE Transactions on*, vol. 58, pp. 4643-4653, 2011.

Z. Ruihua, D. Yumei and L. Yuhong, "New challenges to power system planning and operation of smart grid development in China," in *Power System Technology (POWERCON), 2010 International Conference on*, 2010, pp. 1-8.

Appendix A: Battery Storage System Model

Mathematical model of battery energy storage system of battery models represents 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:

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 Fig.A1, where V_o is battery terminal voltage (S. K. Aditya-F. and D.Das ,2006).

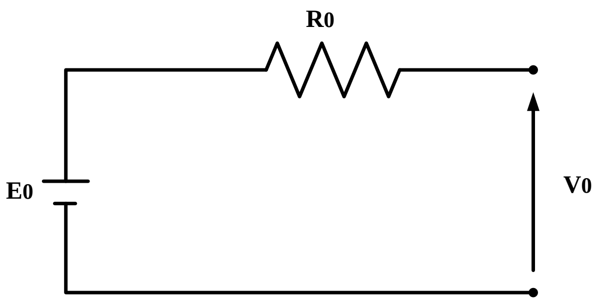


FIG. A1 BATTERY SIMPLIFIED MODEL

Since battery internal resistance varies with temperature and depends 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 some circuit calculation or simulation where the energy from E_o is assumed to be unlimited.

Thevenin Model

The second most common used model is the Thevenin battery model which includes an ideal no load battery voltage *(Eo)*, internal resistance *(R)*, capacitance *(C0)* and over-voltage resistance (R_0) as shown in Fig. A2 (S. K. Aditya-F. and D.Das, 2006; O. Termblay; L-A. Dessaint; and and A-Illah Dekkiche, 2007). 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 assumes that the elements are all constant although all the values are function of battery conditions.

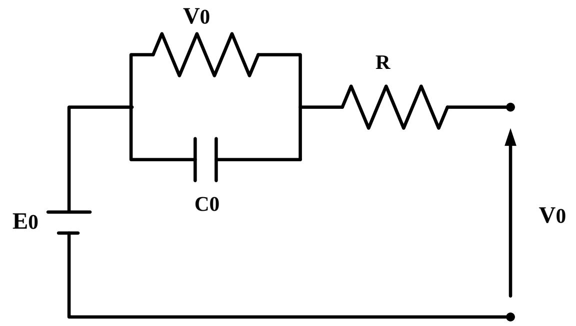


FIG. A2 BATTERY THEVENIN MODEL

Modified Model

The simplified model is modified to take battery state in consideration by replacing the constant voltage source with controllable voltage source which changes battery with no load voltage according to state of charge as shown in Fig.A3. The value of E0 is changed depending on battery current, battery extracted capacity and low frequency current dynamic. (Sel) represents the battery status mode whether it is charge or discharge. The controllable voltage source voltage is calculated as follow (O. Termblay; L-A. Dessaint; and and A-Illah Dekkiche, 2007):

During charging conditions

$$f_1 = E_0 - K.\frac{Q}{Q-i(t)}.i_d - K.\frac{Q}{Q-i(t)}.i_t + A.\exp(B.i(t)) \quad \text{(A-1)}$$

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

$$f_2 = E_0 - K.\frac{Q}{i(t)+0.1Q}.i_d - K.\frac{Q}{Q-i(t)}.i_t + A.\exp(B.i(t)) \quad \text{(A-2)}$$

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)

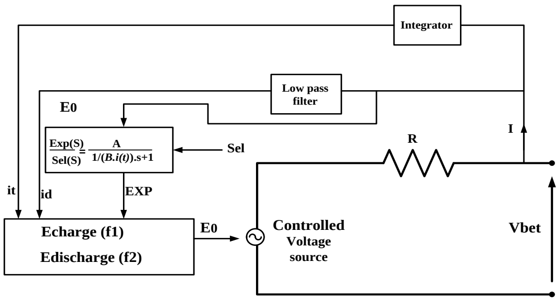


FIG. A3 BATTERY MODIFIED MODEL

Appendix B: Nomenclature

BESS	Battery energy storage system
CO_2	Carbon dioxide
FACTS	Flexible ac transmission systems devices
WF	Wind farm
VSC	Voltage source converter

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