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Comparison of Dynamic Models of Battery Energy Storage for Frequency Regulation in Power System

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Abstract—The paper investigates the use of frequently discussed battery energy storage system (BESS) models for frequency regulation studies. Integration of a large number of renewable generation sources results in increased uncertainty in electric power generation, requiring, among the others, more frequency regulation services than before. The battery energy storage system models are compared and evaluated to assess their suitability for frequency regulation studies. The accuracy and complexity of BES models reported in the past are also discussed.

Index Terms—Battery energy storage systems, Load frequency control (LFC), Battery models

I. INTRODUCTION

The operation of an electric power system is a complex process of forecasting the demand for electricity, and scheduling and operating a large number of power plants to meet that varying demand in real time. At every instant, electrical power generation should match power consumption to keep system frequency constant.

The integration of renewable energy sources reduces the dependence on fossil fuels and greenhouse gas emission but increases variability and uncertainty in electric power generation. It is estimated that for every 10% wind penetration, a balancing power from other generation sources equivalent to 2% to 4% of the installed wind capacity is required for a stable power system operation [1]. Thus, with more penetration of intermittent renewables, the power system operation will become more complex and will require additional balancing power. As a result of this, there have been serious concerns over the safe and reliable operation of power systems with large penetration of renewable sources and reduction in conventional generation.

Effective energy storage can match total generation to total load precisely on a second by second basis. Energy storage can facilitate load leveling for generators, load leveling for postponement of grid upgrade, frequency regulation, and power quality. Conventional generators may take several minutes or even hours to come online and will consume fuel

even when providing a spinning reserve, i.e., when they are on standby.

There are a variety of energy storage options, each with unique operational performance, and durability characteristics. Rated capacity varies from I kW to 1GW, and discharge time at rated capacity varies from seconds to hours. Similarly, the response time of available storage technologies varies from a few milliseconds to a few minutes [2].

Frequency regulation (transient and permanent grid frequency stability support) requires low and medium capacity energy storage devices with a response time of tens of seconds [1]. Batteries (lead-acid, NaS) flywheels, supercapacitors have been all deployed for frequency regulation [3].

Battery energy storage has received substantial attention and support as it offers acceptable cost and performance requirements, providing operating and sitting flexibility and possibly requiring short lead time for construction. BESS (battery energy storage system) over-performs conventional reserve suppliers since it can react and fully activate the reserve within 20 ms [2].

Many studies have been performed in the past to demonstrate the effectiveness of battery storage for frequency control, power regulation and spinning reserve [4-6]. There are numerous factors like battery type, charge, and discharge rate, temperature, and state of charge that might affect dynamic behavior of a battery. Consequently, many types of models have been proposed for BESS in the literature [7-10].

The paper reviews some of the most frequently used battery models and presents the first comparative analysis of these models – to assess their merits for application in frequency regulation studies. The models are compared in terms of their accuracy and requirement of data.

The obtained results demonstrate that the nonlinear battery model is more accurate than other battery models. However, the use of this model requires data from battery discharge curve which can be a demanding task. On the other hand, battery modelled as a voltage source considering the state of charge is simple and accurate enough for load frequency studies.

II. DYNAMIC MODELS FOR BATTERY ENERGY STORAGE

A battery energy storage system (BESS), usually consists of a battery bank and a power converter that interfaces the battery bank to the AC network. A variety of battery energy storage models exist. In this section, brief overviews of most

commonly used BESS models are presented.

A. Thevinen Model

The first attempt to develop a dynamic model of a battery energy storage was made by Beck et al in 1976 [7, 8]. In this model, presented in Fig. 1, BES is represented by a voltage source in series with a parallel RC circuit. It is a simple way of demonstrating the behavior of battery voltage V_b. It contains electrical values of no-load voltage V_{oc}, internal resistance R_1 and overvoltage (parallel combination of C_1 and R_2).
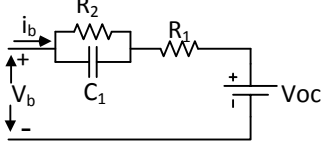

Fig. 1: Thevenin Model of Battery Energy Storage (adapted from [7])

Although this model can describe the outer behavior of a BES correctly, it is incomplete because values of R_1, C_1, and R_2 are not constant as modeled. In fact, they are functions of various battery conditions such as state of charge, battery storage capacity, the rate of charge/discharge, environmental temperature, age/shelf life [8].

B. Battery Equivalent Circuits

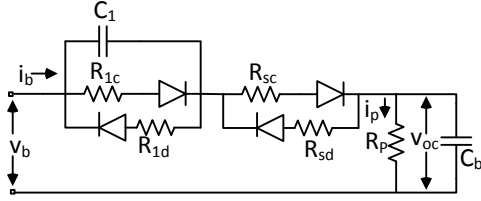Salameh et al presented a mathematical model in 1992 [8], presented in Fig. 2.

Fig. 2: Battery Equivalent Circuit (adapted from [8])

Where C_1 is the overvoltage capacitance, C_b the is battery capacity, i_b the current source, i_p the parallel current, R_{ic} and R_{id} charge and discharge overvoltage resistance, R_p the self-discharge resistance, R_{sc} and R_{sd} are internal resistance for charge and discharge, V_b is the battery voltage, and V_{oc} is open circuit voltage.

This model was developed using nonlinear elements and allows a continuous evaluation of battery performance [8, 11]. The model components were found using manufacturing specifications and experimental tests. The model takes into account self-discharge, battery storage capacity, internal resistance, overvoltage and environmental temperature.

1) BES Equivalent Circuits with Converter

In 1995, Liu et al combined characteristics of battery equivalent circuits and converter to construct a dynamic model of BES [9].

To enable the BES model to be easily utilized in stability analysis of a power system, the model was also presented in frequency domain, shown in Fig. 3.

Where V_t is the BES terminal voltage, E_{DO} is ideal no-load DC voltage of the converter, X_{co} is the commutating resistance of the converter, R_{BT} and R_{BS} are the battery connecting resistance and internal resistance, R_{B1} and C_{B1} are resistance

and capacitance at charging and discharging, C_{BP} is the battery capacitance.
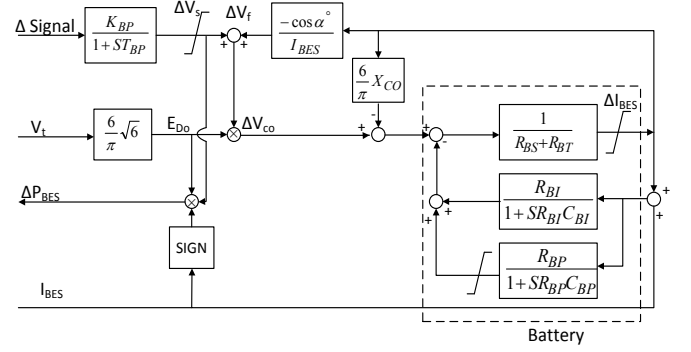

Fig. 3: Dynamic Model of (battery equivalent circuits) BES (adopted from [9])

2) Incremental BES Model

Later in 1999, Aditya et al [10] proposed an incremental BES model that is based on battery equivalent circuits. It is very similar to the model proposed by Liu et al. The only difference is a terminal voltage of the battery is not considered as an input signal in this model.
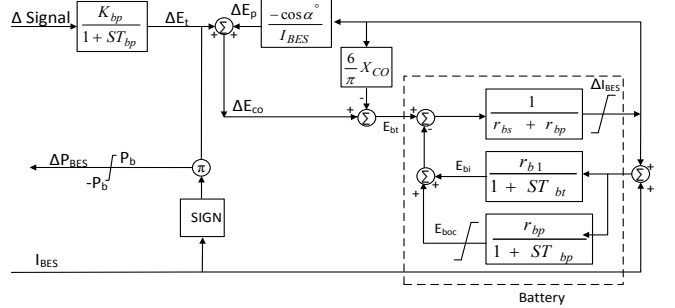

Fig. 4: Incremental BES Model (adapted from [10])

This model has been widely used for load frequency control studies [12, 13].

Although constant current control operating mode is most efficient for a BES, in load frequency control, the BES is operated in constant power mode [14]. After linearization, small change in power of the BES can be written as

$$\Delta P_{BES} = V_{co}^0 \Delta I_{BES} + I_{BES}^0 \Delta V_{co} \tag{1}$$

$$Where\ V_{co} = E_{DO}\cos\alpha \tag{2}$$

ΔV_{co} can be decomposed into two components (a) $E_{DO}\ \Delta V_f$ corresponding to power deviation caused by ΔI_{BES} and (b) $E_{DO}\ \Delta V_s$ corresponding to the system disturbance.

$$\Delta P_{BES} = V_{co}^0 \Delta I_{BES} + I_{BES}^0 E_{DO}(\Delta V_f + \Delta V_s) \tag{3}$$

and

$$\Delta P_{BES} = I_{BES}^0 E_{DO}\Delta V_s \tag{4}$$

When $$\Delta V_f = \frac{-\cos\alpha^0}{I_{BES}^0}\Delta I_{BES} \tag{5}$$

Where $$\Delta V_s = \frac{K_{BP}}{1+ST_{BP}}\Delta\,Signal \tag{6}$$

Where K_{BP} and T_{BP} are control loop gain and measurement device time constant respectively. From (4) and (6) it can be deduced that output of a battery is a function of voltage and change in the feedback signal. The feedback signal is a change in frequency in load frequency control (LFC) studies. This reduces the incremental BES model and BES equivalent circuits model to a simple first-order lag model when voltage E_{DO} is considered constant. It is to be noted that in LFC studies it is a general practice to consider voltage a constant.

C. Non-Linear Battery Model

Shephard developed an equation to describe the electrochemical behavior of a battery directly in terms of its terminal voltage, open circuit voltage, internal resistance, discharge current and state of charge in 1965 [15]. The model based on this equation represents charged and discharged characteristics of a battery. However, it generates an algebraic loop problem in closed-loop simulations of modular models [16].

In 2007, a non-linear battery model was proposed in [16], shown in Fig. 5. This simulation model uses only battery state of charge (SOC) as a state variable to avoid algebraic loop problem. In this model, the internal voltage of the battery is not fixed and is dependent on charging or discharging current.

Where E is no-load voltage, E_0 is battery constant voltage, K is polarization voltage, Q is battery capacity, I is Battery current, A is exponential zone amplitude, B is exponential zone time constant inverse and $\int idt$ = actual battery charge.
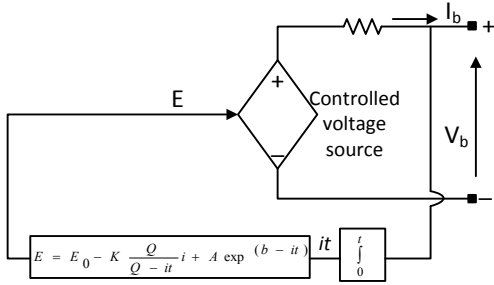

Fig. 5: Non-Linear Battery Model (adapted from [16])

This model can accurately represent the behavior of many battery types. The parameters can be deduced from manufacturer's discharge curve [17].

D. DC Voltage Source in Series with a Resistor

Studies presented in [18, 19] modeled the battery energy storage as a DC voltage source in series with a current controlled inverter (CCI) in an islanded microgrid.

The state of charge for charging and discharging of a battery, in addition, to the DC voltage source in series with an inverter is modeled in [20-22]. All these studies dealt with frequency stability in micro-grid systems.

1) First order Lag model

Simplification of battery model to a first order system has been preferred in many studies [23-26].

Using this simplified model, the effect of a battery energy storage system, which can supply 30 MW for 15 minutes, on frequency control in Israel Electric Corporation is studied.

Performed analysis indicated that battery energy storage can dramatically reduce (6 times less) frequency fluctuations resulting from sudden demand variations [23].
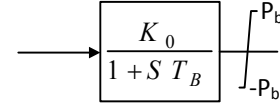

Fig. 6: First Order Model

Redox flow battery (RFB) was modeled in [26, 27] by first order model. It is shown that RFB unit suppresses peak frequency deviations and continue to eliminate steady state error of frequency deviations.

2) First order model with state of the charge

First order model with state of charge, presented in Fig. 7 has been used in many studies [28-32].

An optimized scheduling of a hybrid wind-diesel system with a BES in an isolated power system has been presented in [28] using first order model of a battery with the state of charge.
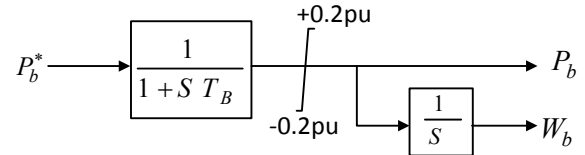

Fig. 7: First Order Model with State of Charge (adopted from [28]

A load frequency control method in wind power generation with a battery storage system is proposed in [30], and battery storage system is represented by the first-order model with state of charge. The method adjusts output of BES according to present state of the charge and applies H_∞ control to generator controller to achieve robust control considering parameters fluctuations generated by state variations in the power system.

III. TEST SYSTEM

The effect of different battery energy storage system models on LFC studies is investigated in an isolated 2GW classic power system with reheat thermal unit. The transfer function model of the classical system is presented in Fig. 8. The capacity of battery energy storage system considered in these studies is 1.15MWh, and it is assumed that BES can provide a maximum power output of 90MW for 46 seconds. The simulations are performed in Matlab/Simulink.

The frequency response of the classical system with each battery model, discussed in Section II, with five cascaded disturbances is simulated. Each of these disturbances is a 0.05p.u increase in the load. Table I presents parameters of the system.

A variety of controls for battery energy storage has been proposed in the literature [22, 31]. Since the aim of this paper is to demonstrate the effect of different battery storage models on load frequency studies, proportional control is used with BES system. The use of PI controller makes the BES contribute in load leveling.
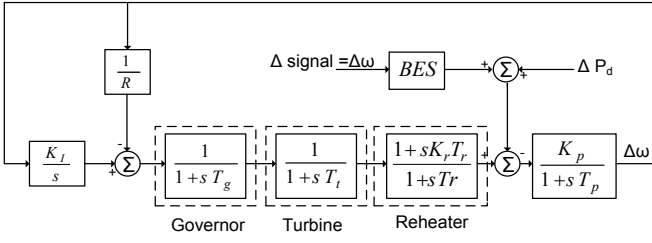
Fig. 8: Transfer function model of a classical system

Table I: Parameters of the classical system

Parameter	Value	Parameter	Value
K_p	120	T_t	0.3
T_p	20	T_r	10
D	1	K_r	0.5
K_t	1	R	2

IV. RESULTS AND DISCUSSIONS

1) Thevenin Model versus Voltage Source in Series with a Resistor

First, the battery energy storage system is represented by Thevenin model and five cascaded disturbances in the load are introduced. The system frequency response to these variations in load is shown by the red line in Fig. 9.
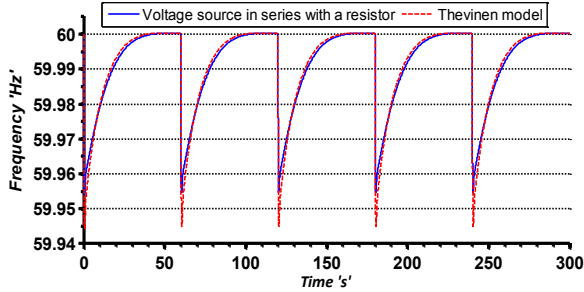

Fig. 9: Comparison of Thevenin model and voltage source in series with a resistor

Following this, BES model is replaced by a voltage source in series with a resistor. Same five cascaded disturbances in the load are applied, and frequency response of the system is recorded, presented in Fig. 9.

It can be observed that with both types of BES models, the trajectory followed by system frequency is very similar, except the first dip in system frequency when the disturbance is introduced in the system. The dip in frequency with Thevenin model is slightly bigger than voltage source in series with a resistor.

2) Battery Equivalent Circuits versus Voltage Source in Series with a Resistor

The frequency response of the system with equivalent circuits model and voltage source in series with a resistor is presented in Fig. 10. Blue curve shows the system frequency when BES is modeled with a voltage source in series with a resistor, and the red curve represents the frequency of the system when BES is represented by battery equivalent circuits.

It can be observed that the difference in system frequency response due to different battery models becomes more noticeable as the number of disturbance increases. Battery equivalent circuits model takes into consideration the energy stored in the battery, as the stored energy decreases battery provides less power (see Fig. 11) increasing the dip in system frequency. After every disturbance, the response of the system with equivalent circuit model becomes more similar to the system without battery, i.e., bigger dips in the system frequency. The frequency support of BES decreases after each disturbance as the stored energy in the battery reduces.

It is to be noted that the control system of the battery is modeled with a proportional controller while the system without battery has an integral control in the secondary loop.
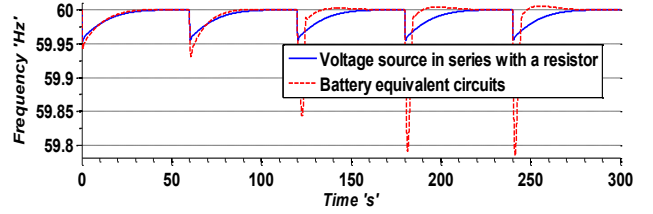

Fig. 10: Comparison of battery equivalent circuits model and voltage source in series with a resistor
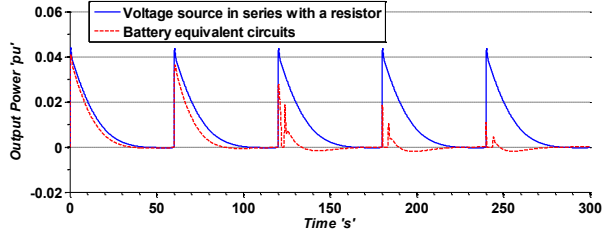

Fig. 11: Power supplied by battery equivalent model and voltage source in series with a resistor

3) Incremental Model

As explained in the previous section both BES models, incremental and battery equivalent circuits reduce to the same model in LFC studies. Simulations results with battery equivalent circuits model are presented in the previous section that eliminates the need to simulate the incremental model.

4) Non- Linear Model versus Voltage Source in Series with a Resistor

Fig. 12 compares the system frequency response when BES is represented by a non-linear model (red curve) and by a voltage source in series with a resistor (blue curve). It is evident from the figure that following the first disturbance, system frequency behavior with both types of model is nearly identical. After the second and third disturbance, there is a slight difference in the frequency dip, and fifth disturbance leads to a much bigger dip in system frequency if the nonlinear model of battery is used.

Similar to battery equivalent circuits, the difference between the non-linear BES model and voltage source in series with a resistor model becomes more visible when the stored energy in the battery is reduced.
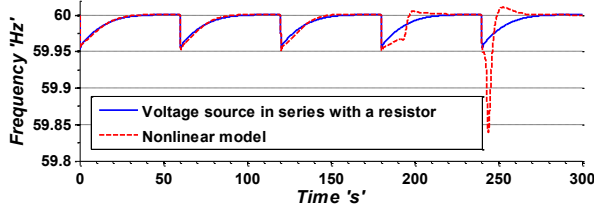
Fig. 12: Comparison of non-linear model and voltage source in series with a resistor

5) First-order Model versus Voltage Source in Series with a Resistor

It is standard practice to a model voltage source with a resistor as a first order model in LFC studies. Hence, first order model is not simulated in these studies.

6) First order Model with state of charge versus Voltage Source in Series with a Resistor
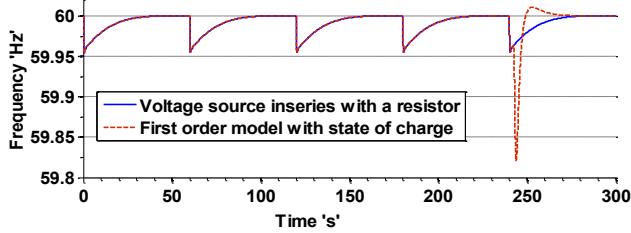

Fig. 13: Comparison first order model with state of charge and voltage source in series with a resistor

Fig. 13 compares the response of system frequency when BES is represented by the first order model with state of charge, and a voltage source in series with a resistor. In first order model with state of charge, the power produced by the battery is not a function of charge (the power provided by the BES stays constant). However, when all the stored energy is consumed, the output power of the battery is reduced to zero.

It can be observed that the frequency response of the system is identical with both types of BES models. The difference in the response (at 250s time stamp) only appears when the battery is fully discharged.

The output power of the battery depends on charging and discharging currents. For a better understanding of the dynamic behavior of different battery models, the output power of discussed models under the same discharging current have been shown in Fig. 14.

Fig. 14a demonstrates that the battery models can be grouped into two categories:

Group 1: Voltage source in series with a resistor, Thevenin model and first order model with state of charge.

Group 2: Nonlinear model and battery equivalent circuits

In group 1 the power outputs of the voltage source in series with a resistor and first order model with state of charge are the same until the stored energy is consumed. It can also be observed that power output of Thevenin model follows power output of voltage source in series with a resistor closely.

The power output of group 2 models differs significantly from group 1 models, this difference in the output power increases with the discharge of the battery. It can also be

noticed that the power output of battery equivalent circuits starts to deviate from power output of the nonlinear model, and this deviation increases with time.
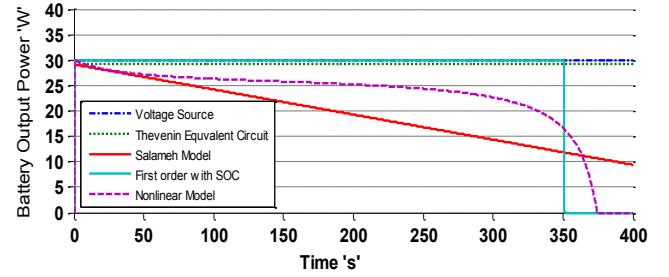

Fig. 14a: Output power for different battery models when they have been discharged by a constant 30A current.
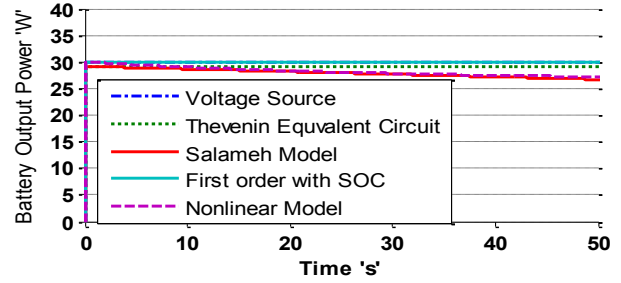

Fig. 14b: Output power for different battery models when they have been discharged by a constant 30A current.

Focusing more closely, Fig. 14b shows that different battery models have a very similar response in first 20 seconds after the disturbance, the power output of different battery models is nearly same. After 20seconds, the output power of group 2 models starts to differ from group 1 models and at 50 seconds 10% reduces it compared to the output power of group 1 models. Primary frequency control is normally within the 20-50sec time scale, and in the case of fully charged battery, it would be difficult to see any significant difference in the response of different battery models.

V. CONCLUSION

This paper presented the first comparative analysis of the most commonly used battery energy storage system models to assess their suitability for load frequency control studies. These comparative studies are performed using a simple small power system model. It is observed that frequency response of the system with different BES models is similar after the first disturbance. The frequency response of the system with battery equivalent circuits shows bigger frequency dip after first disturbance, and the depth of the dip becomes bigger after each disturbance. Non-linear battery model and first order model with state of charge follows closely the frequency response trajectory of the voltage source in series with a resistor model until the battery is discharged.

Based on these studies, it can be concluded that the most important battery parameters that can significantly affect LFC studies is the state of the charge. Other parameters like charging or discharging process, internal resistance and temperature dependency or converter model do not have any appreciable effect on LFC studies. The dynamics of frequency

regulation is slow so that it does not require detailed modeling of fast dynamic processes in the battery.

The nonlinear battery model is more accurate,however, it could be challenging to obtain required battery data from discharge curve.

Simple voltage source considering the state of charge is simple and accurate enough for load frequency studies.

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