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A Novel Generic Battery Modeling Approach for Power System Simulation Applications

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ABSTRACT

Very large capacity energy storage systems are required in power systems for utility shaping when renewable energy systems like wind farms are not supporting sufficient generation. Energy storage systems are indispensible during evacuation problem in existing grid structure. For addressing power quality aspects also, quick responsive energy storage systems are requisite. In these contexts, before practical implementation of energy storage systems, for a particular or combined application, its characteristics are to be simulated in power system environment to suit for the specific application. In this perspective, the various battery modeling are briefed and a novel generic battery modeling approach which will be useful in power system simulation application is presented in this paper. The contribution through this work is, real time physical parameters of battery are incorporated in look-up table. Those values are read during simulation to compute standard electrode potential of battery. As future scope of work, real-time interfacing of physical parameters of battery can be implemented during simulation. Vanadium redox flow battery and lithium-ion battery are simulated using the generic battery modeling approach and their results presented, comparing their suitability for utility shaping, power quality enhancement aspects and distributed grid technology application.

Indexing terms/Keywords

Entropy, Enthalpy, Energy storage system, Electrochemical model, Analytical model, Electric circuit model, Generic model

Academic Discipline And Sub-Disciplines

Electrical Engineering and Electrochemistry

SUBJECT CLASSIFICATION

Electrical Engineering and Chemistry Subject Classification

TYPE (METHOD/APPROACH)

A novel generic battery model development that incorporates enthalpy and entropy blocks; Simulation results validation; Suitability of the proposed model for power system simulation application justification

1. INTRODUCTION

Renewable power volume is increasing day-by-day throughout the globe with the advent of implementation of more wind farms and solar power systems to ensure green and sustainable energy. The aggregated power output of the wind farm fluctuates due to wind variation. Similarly, the output of solar power plant also varies with incident lumens variation. The existing distribution and transmission grids are weak at most places where renewable power penetration is high. Integration of renewable power at such weak points of the grid has worsened the power quality [1]. To overcome the power fluctuations and to mitigate the power quality issues arising of renewable power integrated to power grid, battery energy storage supplement is one of the viable options [2]. Despite of the above mentioned specific applications, the battery energy storage systems can also be used for storing renewable power during periods of low demand and release it during periods of high demand and also provide active and reactive power support when connected with a power conditioning system that could operate in all four quadrants at its terminals. This paper is constrained to discussions related to a novel generic modeling approach of battery energy storage system for power system simulation applications. Sections 2 to 4 discuss the various battery energy storage modeling approaches. Section 5 discusses the generic modeling approach of battery energy storage systems. This section also presents the generic modeling approach as applied to vanadium redox battery and lithium-ion battery. Section 6 presents the simulation result of these models as used with a wind farm integrated to radial power system. The performance comparison based on the simulation results of these models are tabulated which presents the suitability of a battery type for specific application.

2. ELECTROCHEMICAL MODELING

The electrochemical modeling is based on the electrochemistry of the batteries. These models describe the physical and chemical processes taking place inside the battery in detail. [3-4] presents identification of the full-set of the reduced-order electrochemical battery model parameters by using noninvasive genetic algorithm optimization on a fresh battery. To the context of generic battery modeling approach, the concept of arriving at the standard reduction potential from the electrochemistry of battery is analyzed. The standard reduction potential computation involves the application of Gibb's free enthalpy and conservation of energy, and empirical parameters found in electrochemical tables [5].

The standard Gibbs free enthalpy of reaction ΔG^o which represents the change of free energy that accompanies the formation of $1\,M$ of a substance from its component elements at their standard states: $25^o\,C, 100\,kPa$ and $1\,M$ [6] is introduced here:

$$\Delta G^o = \Delta H_r^o - T\Delta S_r^o \; [kJ/mol] \tag{1}$$

Where the standard reaction enthalpy ΔH_r^o is the difference of molar formation enthalpies between the products $\Delta H_{f,product}^o$ and the reagents $\Delta H_{f,reagent}^o$:

$$\Delta H_r^o = \sum_{products} \Delta H_{f,product}^o - \sum_{reagents} \Delta H_{f,reagent}^o \; [kJ/mol] \tag{2}$$

And the standard reaction entropy ΔS_r^o is the difference of molar formation entropies between the products $\Delta S_{f,product}^o$ and the reagents $\Delta S_{f,reagent}^o$:

$$\Delta S_r^o = \sum_{products} \Delta S_{f,product}^o - \sum_{reagents} \Delta S_{f,reagent}^o \; [J/mol \cdot K] \tag{3}$$

Then, when the thermodynamical data from look-up table are substituted in the product and reagent expansions in the above equations, the standard reaction enthalpy ΔH_r^o and the standard reaction entropy ΔS_r^o are obtained.
The conservation of energy relates the change in free energy resulting from the transfer of n moles of electrons to the difference of potential E:

$$\Delta G = -nFE \; [J/mol] \tag{4}$$

Therefore, the standard reduction potential E^o is obtained when ΔG^o is introduced in Nernst equation with the values of the standard reaction enthalpy (2) and entropy (3) into the reformulated (4):

$$E^o = -\frac{\Delta G^o}{nF} = -\frac{\Delta H_r^o - T\Delta S_r^o}{nF} \quad [V] \tag{5}$$

Once the standard reduction potential E^o is determined from the thermodynamical principles, it can be integrated in the analytical modeling block.

3. ANALYTICAL MODELING

Since we are concerned about the battery potential stability for utility shaping application and charge-discharge changeover time to address the power quality issues in power systems, the kinetic battery modeling approach, which uses the chemical kinetic process as its basics, is adopted. It uses the state-of-charge (SOC) of battery at every instant of simulation. Real-time estimation of the state of charge (SOC) of the battery is a crucial need [7]. Article [8] presents an aggregated battery circuit model with the open circuit voltage as a nonlinear function of the state of the charge (SOC). Paper [9] presents a higher fidelity battery equivalent circuit model incorporating asymmetric parameter values presented for use with battery state estimation algorithm development, particular focus is given to state-of-power (SOP) or peak power availability reporting. SOC is an indication of how much energy is stored in the battery; it varies from 0 (discharged state) to 1 (charged state). The energy storage is dependent on battery material concentration and proton concentration. The battery equilibrium potential or otherwise called the battery internal voltage is given by [10]:

$$E_c = E^o + 0.0592 log\left(\frac{SOC}{1 - SOC}\right) \tag{6}$$

The stack voltage is given by:

$$E_s = n1.\left(E^o + 0.0592 log\left(\frac{SOC}{1 - SOC}\right)\right) \tag{7}$$

Where $n1$: number of cells

Depending upon the energy requirements from the energy storage system, the number of cells $n1$ can be chosen.

Table 1. Comparison of various battery modeling approaches

Sl. No.	Various battery models	Positive aspects	Remarks
1.	Electrochemical model	Most accurate	Complex and difficult to configure
2.	Analytical model	High level of abstraction; much easier to use	Battery is modeled using only few equations
3.	Electrical circuit model	Computationally simpler	Less accurate, 10% error

4. ELECTRICAL CIRCUIT MODELING

When the anode and cathode of the battery are connected through external load, flow of electrons is facilitated through load from anode to cathode. There is always opposition to the flow of electrons and is designated by internal resistance of the cell. This resistance is susceptible to temperature changes, which has to be accounted. In the electric circuit model of a cell, this resistance has to be represented in series with the standard reduction potential of the cell. When the model is extended to battery level, the number of cells $n1$ has to be accounted for representing battery potential and resistance. The battery voltage depends on state-of-charge of battery, length of time since it was charged and temperature, which has to be accounted in the modeling. The electrodes are separated by the membrane and electrolyte, which has to be represented by a parallel capacitor. So in the electrical circuit models of the battery, the following are to be incorporated:

- The battery potential, accounted from standard reduction potential and other parameters discussed above for $n1$ number of cells,
- The internal resistance and its temperature dependence,
- The equivalent capacitance of electrodes of the battery and
- Voltage versus state-of-charge look-up table.

And for specific battery modeling, required changes can be incorporated. The comparison of various battery modeling approaches is presented in Table 1.

5. GENERIC MODELING

The positive aspects of the modeling approaches briefed above are to be integrated to develop a generic battery model. Non-chemically based partially linearized (in battery power) input–output battery model [11], multi-resolution modeling approach using wavelet neural networks [12], novel hybrid battery model, which takes the advantages of an electrical circuit battery model to accurately predict the dynamic circuit characteristics of the battery and an analytical battery model to capture the nonlinear capacity effects for the accurate SOC tracking and runtime prediction of the battery [13], and [14-17] are some of the works that presents inputs for generic battery modeling approach. Article [18] presents comparison and parameterization process of dynamic battery models for cell and system simulation, [19] presents identification algorithms that capture individualized characteristics of each battery cell and produce updated models in real time. The algorithmic flowchart for the generic battery modeling approach proposed is presented in Figure 1. First the type of battery is selected. For generic modeling of battery energy storage systems, a look-up table with thermodynamical data for different compounds for various batteries is developed, and for a particular battery type selected, relevant thermodynamical data are read from the look-up table into the Enthalpy and Entropy blocks and simulated to compute the standard reduction potential E^0 for the battery type selected.

This standard reduction potential value and SOC value are used in the Nernst equation to arrive at the internal cell voltage E_c. Multiplying the number of cells $n1$ gives the stack voltage E_s. From the various battery electric models available, a type which is suitable for specific application simulation is selected. The electrical circuit parameters are read for the type selected. The internal battery voltage in the electric circuit model is substituted with the stack voltage arrived from electrochemical and analytical modeling. The complete battery model of required type is developed and it can be used for specific power system simulation application.

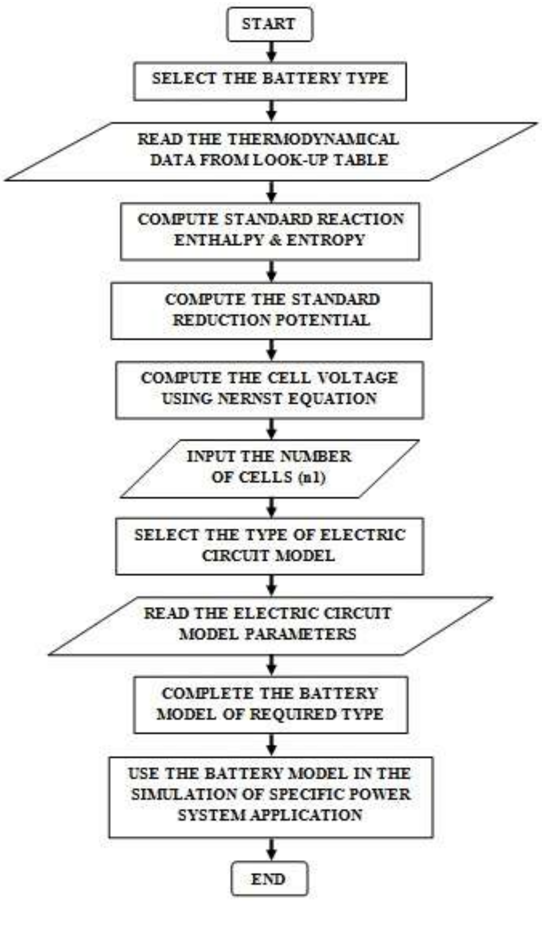


Fig 1: Algorithmic flowchart of generic modeling approach

5.1 Generic modeling approach as applied to vanadium redox and lithium-ion battery

5.1.1 Electrochemical modeling

The overall reaction on the lithium-ion cell [20] is given by (8) and vanadium redox battery [21] is given by (9)

$$C + LiCoO_2 \leftrightarrow LiC_6 + Li_{0.5}CoO_2 \quad (8)$$

$$V^{2+} + VO_2^{+} + 2H^{+} \rightleftarrows VO^{2+} + V^{3+} + H_2O \quad (9)$$

Table 2. Thermodynamical data for some vanadium compounds at 298.15 K. Values in parentheses are estimated [22].

FORMULA	STATE	$\Delta H_f^o\left[\frac{kJ}{mol}\right]$	$\Delta G_f^o\left[\frac{kJ}{mol}\right]$	$S_f^o[\frac{J}{mol}\cdot K]$
V^{2+}	Aqueous	(-226)	-218	(-130)
V^{3+}	Aqueous	(-259)	-251.3	(-230)
VO^{2+}	Aqueous	-486.6	-446.4	-133.9
VO_2^+	Aqueous	-649.8	-587	-42.3
H_2O	Aqueous	-285.8	-237.2	69.9
H^+	Aqueous	0	0	0

When the thermodynamical data from look-up table, for vanadium redox battery values are given in table 2, is introduced into (9), the standard reaction enthalpy ΔH_r^o of the vanadium redox battery reaction (2) becomes:

$$\Delta H_r^o = \Delta H_{f,VO^{2+}}^o + \Delta H_{f,V^{3+}}^o + \Delta H_{f,H_2O}^o - \Delta H_{f,V^{2+}}^o - \Delta H_{f,VO_2^+}^o - \Delta H_{f,H^+}^o \quad (10)$$

$$= -155.6 kJ/mol$$

Similarly, the standard reaction entropy ΔS_r^o is obtained when these thermodynamical data are introduced into (3):

$$\Delta S_r^o = \Delta S_{f,VO^{2+}}^o + \Delta S_{f,V^{3+}}^o + \Delta S_{f,H_2O}^o - \Delta S_{f,V^{2+}}^o - \Delta S_{f,VO_2^+}^o - \Delta S_{f,H^+}^o \quad (11)$$

$$= -121.7 J/mol\cdot K$$

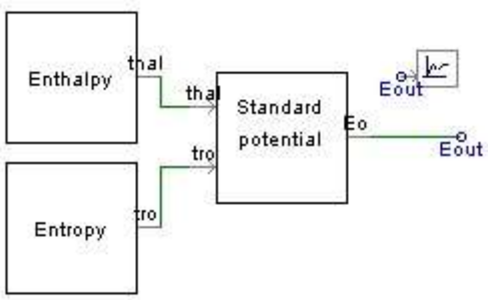


Fig 2: Generic electrochemical model that generates standard reduction potential

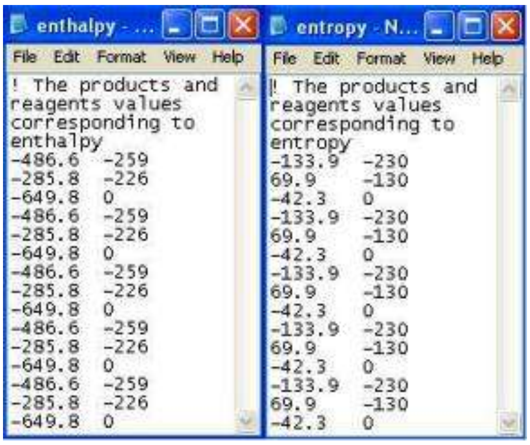


Fig 3: Thermodynamical data from look-up table

Figure 2 shows the generic electrochemical model developed in PSCAD/EMTDC. It comprises the entropy and enthalpy blocks that reads the thermodynamical data from look-up table, shown in figure 3, for the battery type selected. The output of these blocks is given as input to the standard potential calculation block, which outputs the standard reduction potential. The standard reduction potential for vanadium redox battery from this generic electrochemical model is shown in figure 4. The standard reduction potential E^0, from equation (5), for vanadium redox flow battery is 1.23V and similarly for lithium-ion cell is 3.67V at 298.15^o K.

5.1.2 Analytical modeling

The variations in stack voltage can be arrived from the equation (7) of analytical modeling. The stack voltage is dependent on the dynamic SOC of battery and number of cells in the stack. The number of cells n1 is assumed as 500 with SOC varying from 0.1 to 0.9. Figure 5 shows the variations in stack voltage of vanadium redox battery and figure 6 shows the variations in stack voltage of lithium-ion battery for varying SOC.

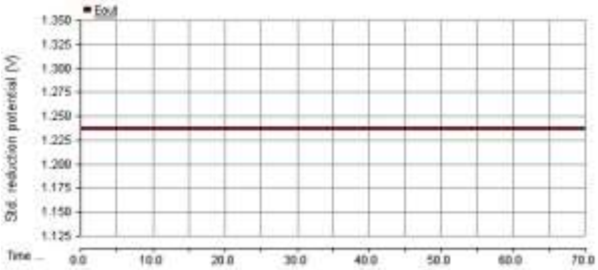


Fig 4: Standard reduction potential $E^0 = 1.23\ V$ generated from Generic model of vanadium redox battery

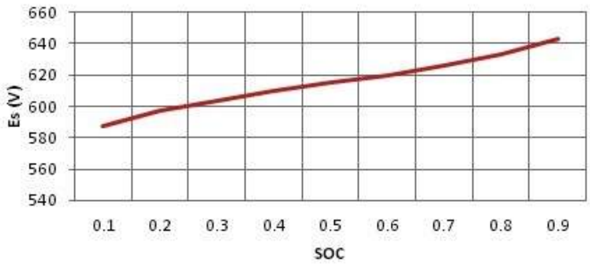


Fig 5: Vanadium redox battery 500 cell stack voltage for varying SOC

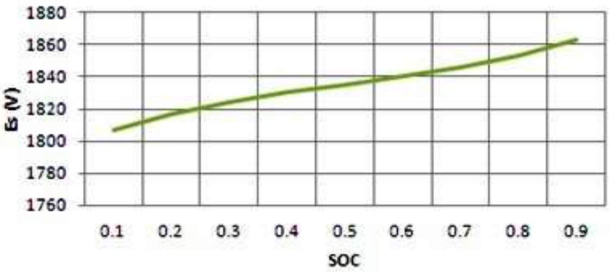


Fig 6: Lithium-ion battery 500 cell stack voltage for varying SOC

5.1.3 Electrical circuit modeling

For vanadium redox battery, the electric circuit model adopted in [23] is used. For lithium-ion battery, the electric circuit model adopted in [24] is used. The modeling and simulation are performed using PSCAD/EMTDC. The electric circuit model of vanadium redox battery is shown in Figure 7, the SOC is being time updated and is given by:

$$SoC_{t+1} = SoC_t + \mathrm{E}_s * I_s * \frac{\Delta t}{W_b} \quad (12)$$

The pump current is given by:

$$I_p = 1.0126 \ln\left(\frac{|I_s|}{SoC}\right) \quad (13)$$

The related parameters are given in Table 3.

Table 3. Characteristics of VRB battery [25]

$n1$ (no. of cells)	R_{fixed}	R_{react}	R_{resist}	$C_{electrode}$
500	25.92Ω	0.07476Ω	0.04984Ω	0.12F

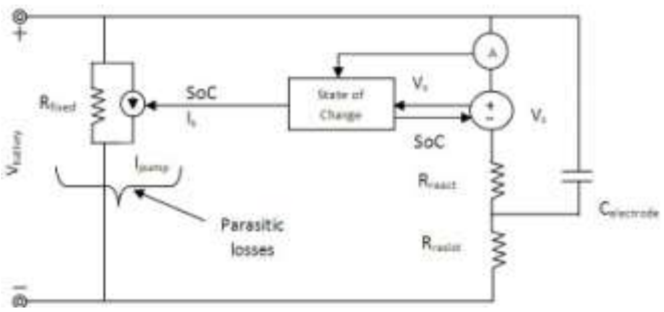


Fig 7: Model of Vanadium Redox Battery

Figure 8 illustrates the model using PSCAD and Figure 9 gives the charge-discharge characteristics of such a model. This model can be used in conjunction with simplified models of the power electronic converter or can be implemented with the detailed model.

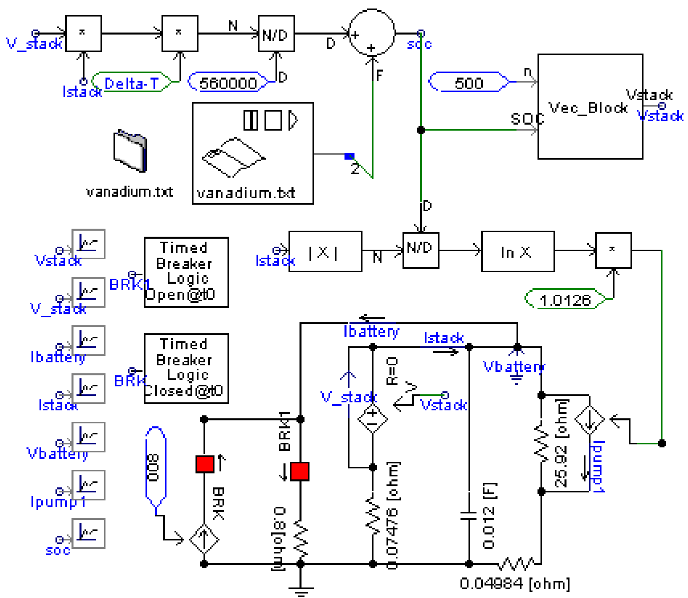


Fig 8: PSCAD model of VRB with charge (800 A), until 60s and discharge (0.8Ω), for next consequent 60s

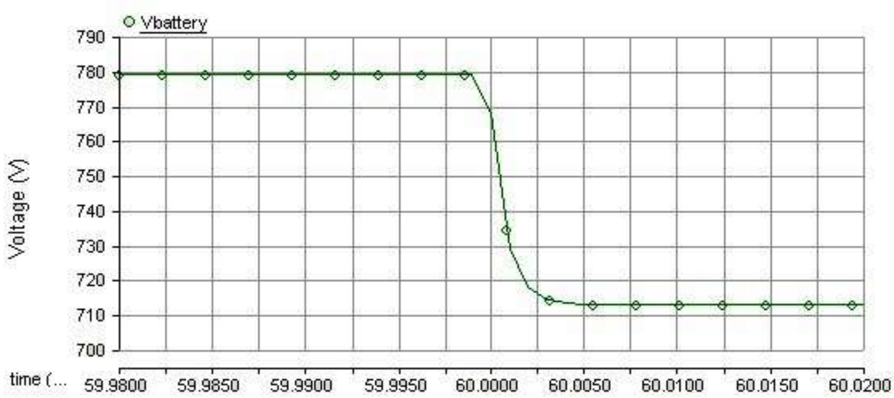


Fig 9: The charge (800 A), until 60s and discharge (0.8Ω), for next consequent 60s, output voltage takes 6ms to reach the steady state.

Table 4. Characteristics of lithium-ion battery [13]

$n1$ (no. of cells)	R_S	R_{T_L}	R_{T_S}	C_{T_L}	C_{T_S}	C_{bcap}
33	0.045Ω	0.0279Ω	0.0304Ω	14890F	1831.7F	126000F

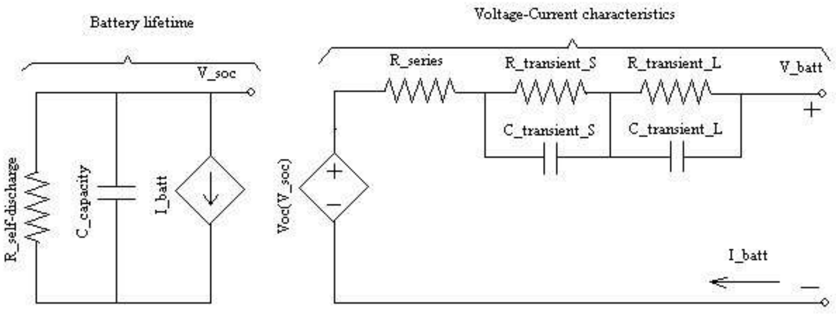


Fig 10: Model of Lithium-ion Battery

The electric circuit model of lithium-ion battery is shown in Figure 10, the capacitor and current-controlled current source at the left models the capacity, SOC and lifetime of battery. On the right, the RC network simulates transient response as in the case of Thevenin-based models. A voltage-controlled voltage source is used to bridge the SOC to open circuit voltage. Figure 11 shows the electric circuit model developed in PSCAD/EMTDC by deriving the ordinary differential equation (14) for the above circuit.

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\left(R_{T\_S}C_{T\_S}\right)^{-1} & 0 \\ 0 & 0 & -\left(R_{T\_L}C_{T\_L}\right)^{-1} \end{bmatrix} x + \begin{bmatrix} -\left(R_{s\_d}C_{bcap}\right)^{-1} \\ -C_{T\_S}{}^{-1} \\ -C_{T\_L}{}^{-1} \end{bmatrix} u \quad (14)$$

$$y = g(x_1) + x_2 + x_3 + R_S u$$

The related parameters are given in table 4. Figure 12 gives the charge-discharge characteristics of such a model. The charge-discharge changeover time of both the vanadium redox and lithium-ion battery is in terms of 'ms' which is a feature that can be exploited for its utilization with grid integrated wind energy conversion systems where the response time required is in terms of 'ms' for stable operation of power grid in events like grid side faults and drastic wind variations.

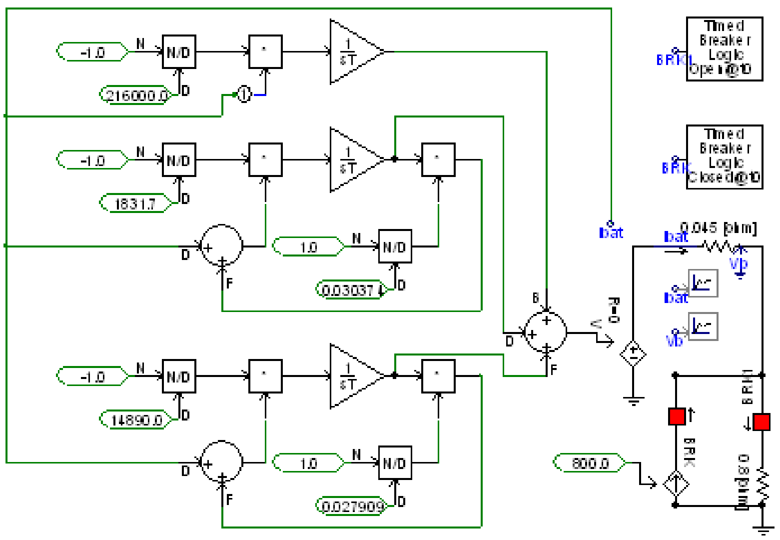


Fig 11: PSCAD model of lithium-ion battery with charge (800 A), until 15s and discharge (0.8Ω), for next consequent 25s

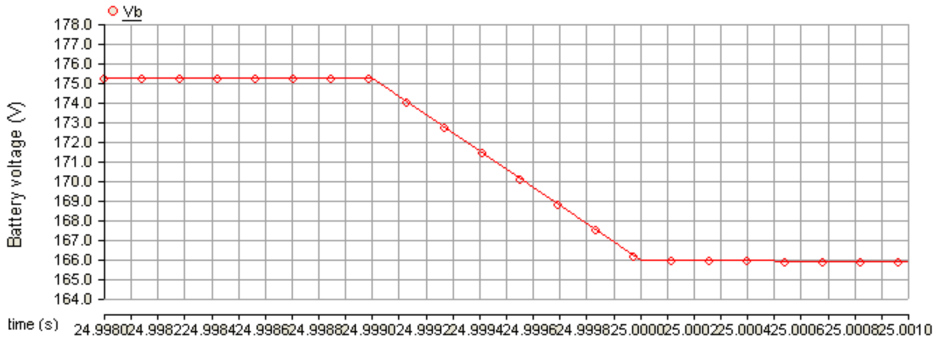
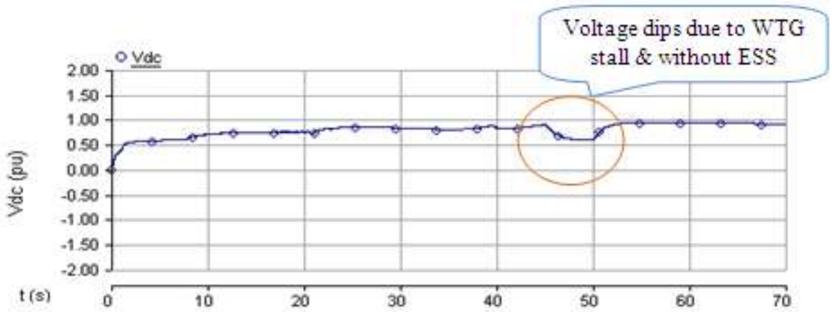


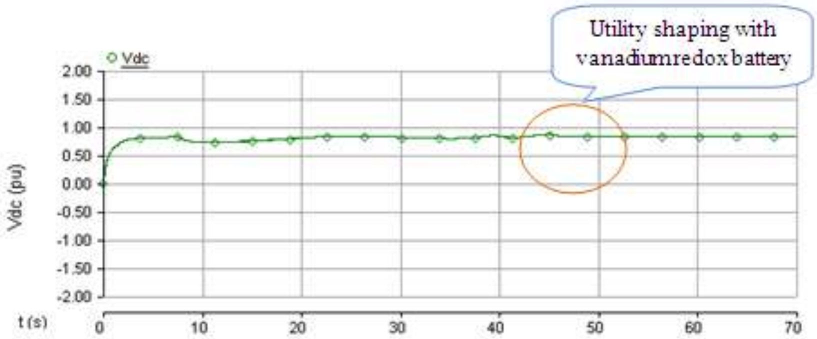
Fig 12: The charge (800 A), until 15s and discharge (0.8Ω), for next consequent 25s, output voltage takes 1ms to reach the steady state.

6. PERFORMANCE ANALYSIS IN POWER SYSTEM SIMULATION APPLICATION

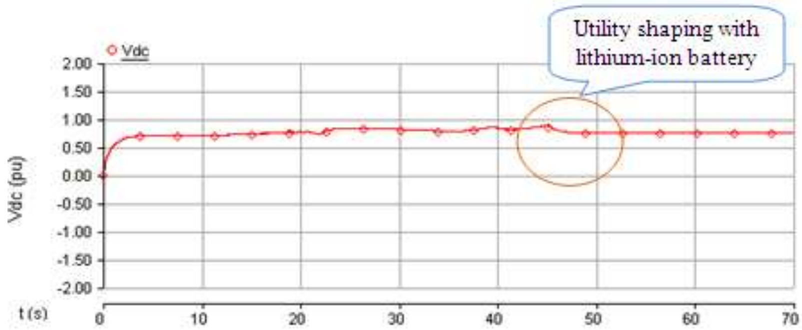
The vanadium redox and lithium-ion battery model derived of applying generic modeling approach is integrated to the radial power system which is supported by a 300 MVA wind farm. The wind variation is simulated such that the wind turbine generator stalls during 45s to 50s. Due to this, a voltage dip arises in dc bus of ac-dc-ac conversion stage. Figure 13 (a) shows dc bus voltage dip for intermittent wind power without energy storage. Figure 13 (b) shows dc bus voltage shaping with vanadium redox battery and (c) with lithium-ion battery.



(a)

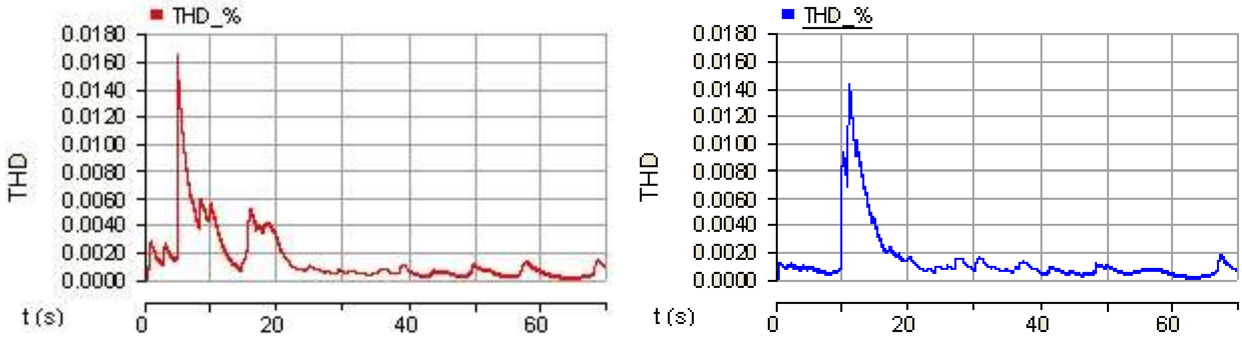


(b)



(c)

Fig 13: DC bus voltage shaping for intermittent wind power from 45s to 50s (a) without energy storage, (b) with vanadium redox battery energy storage and (c) lithium-ion battery energy storage



(a) **(b)**

Fig 14: Voltage total harmonic distortion (THD_V) plots with (a) vanadium redox battery and (b) lithium-ion battery

Table 5. Performance comparison of vanadium redox and lithium-ion battery in the context of generic battery modeling approach

Sl. No.	Parameters	Vanadium redox	Lithium-ion
1	Cell voltage (V)	1.23	3.67
2	Stack voltage (V)	632.8 (500 cells @ 80% SOC)	122.3 (33 cells @ 80% SOC)
3	Charge-discharge changeover time (s)	0.006	0.001
4	Utility shaping	Most suitable, Figure 12(b)	Suitable, Figure 12(c)
5	Power quality addressing	THD_V: 1.42% max (for n=7)	THD_V: 1.68% max (for n=7)
6	Distributed grid technology	Suitable	Most suitable

The total harmonic distortion of voltage (THD_V) of harmonic order 7 measured at bus 1 of utility side where the wind farm power is integrated is shown in Figure 14. The THD is 1.68% maximum at t=5s with vanadium redox battery and the THD is 1.42% maximum at t=12s with lithium-ion battery. But both the THD values are well within the voltage harmonic limits prescribed by the Indian Wind Grid Code [26] and Indian Electricity Grid Code [27]. Table 5 gives the performance comparison of vanadium redox and lithium-ion battery in the context of generic battery modeling approach as applied to power system simulation application.

7. CONTRIBUTIONS, RESULTS AND DISCUSSIONS

7.1 Contributions

i. A novel generic battery model approach that reads the thermodynamical data from look-up table into enthalpy and entropy blocks to dynamically update the standard reduction potential is presented.

ii. The prominent features of various battery modeling approaches are integrated to build a generic battery model through an algorithm for specific application in power systems.

iii. The generic battery model developed is used in wind power integrated to utility grid system to study harmic distortion reduction and utility shaping in the events of intermittent wind.

7.2 Results and discussions

i. The simulation of generic battery models developed are done with PSCAD/EMTDC software. The response time of energy storage systems must be in terms of ‘ms’ to ensure stable operation of wind power integrated to power system in the event of drastic wind variations.The simulation result shows charge-to-discharge and discharge-to-charge changeover time with vanadium species as battery material as 6ms and with lithium ion as 1ms which proves its use in power system simulation applications.

ii. The generic model as used with wind power integrated to power system, shows significant improvement in utility shaping and reduction in voltage total harmonic reduction.

8. CONCLUSION

This paper presents the generic modeling approach of energy storage system integrating the electrochemical, analytical and electrical circuit battery modeling approaches. Such type of models can be simulated to estimate the actual requirement of storage capacity for renewable power applications of stand alone or grid integrated type, before actual implementation, which will optimize the energy storage requirements and hence will be a feasible solution from economic considerations point of view. The charge-discharge transition time of vanadium redox and lithium-ion batteries are in 'ms' which is justified from the simulation results, which is a feature that can be exploited for its utilization with grid integrated renewable energy systems where the response time required is in terms of 'ms' for stable operation of power grid in events like grid side faults and renewable source side variations. From the simulation results, it is also proved that the vanadium redox and lithium-ion batteries support power balance in such events. The total harmonic distortion is also considerably reduced with the use of energy storage systems. As a future scope, after estimation of energy and power to be stored from amount of excess power generated by renewable energy source, a software program that could optimize energy and power requirements and hence the number of cell stacks and volume of electrolyte required can be developed to support mitigation of power quality issues while integrating renewable energy to power grid. Also real-time interfacing of physical parameters of battery can be implemented replacing the look-up table section during simulation studies.

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