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Article:

Energy Storage Systems for PV-Based Communal Grids

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Abstract:

In this paper a review of energy storage systems used with PV power generators are reviewed with a focus on batteries. Merits and demerits of different storage technologies are compared. Batteries are further reviewed, modelled and simulated, with a focus on the four most common battery technologies used with PV systems, i.e., lead-acid (Pb-acid), lithium-ion (Li-ion), nickel metal hydride (Ni-MH), and nickel cadmium (Ni-Cd). Pb-acid batteries are the cheapest and most widely available but it also has the lowest charging/discharging cycles. Ni-MH and Ni-Cd batteries have many similar characteristics with the latter being the most temperature resistant of all batteries. However, there technologies are not widely available and are quite expensive compared to Pb-Acid batteries. Li-ion batteries have the fastest and most discharging/charging cycles and highest efficiencies of up to 99%. However, they are also the most expensive and are also not widely available in developing communities; the merits and demerits of the four battery technologies mentioned above are compared in a table.

Highlights:

- Batteries are the most common types of storage devices used with PV systems
- Pb-acid batteries are the cheapest, most versatile, and most common types of batteries
- Li-ion batteries have higher efficiencies and faster charging/discharging cycles
- Ni-MH and Ni-Cd batteries are the most temperature resistant

Keywords: PV; Communal Grids; Energy Storage; Batteries; Environment

1.0 Introduction:

Energy storage systems are used in decentralized power systems for energy management, i.e., load levelling or peak shaving, for power bridging, and for power quality improvements [1-4]. Energy management functions require the energy storage system to serve for long durations compared to the other functions [1-4]. Power bridging functions require energy storage systems to serve for few seconds to few minutes [1-4]. For power quality improvements, the energy storage systems are required for only fractions of a second [1-4]. The main energy technologies include pumped hydro, compressed air energy storage (CAES), flywheels, superconducting magnetic energy storage (SMES), and electrochemical storage [5-9].

In pumped hydro systems, excess energy during low demand periods is used to pump water from a lower reservoir into an uphill reservoir from where it can be used to generate electricity during high power demands by natural flow of water through turbines back to lower reservoir. In CAES systems compressed air is used to feed a gas turbine to generate electricity when necessary. In flywheels energy is stored in form of mechanical kinetic energy and is converted back into electricity by the

use of a 4-quandrant power converter. SMESs store energy in magnetic fields using supercondicting coils with high magnetic fields. The stored energy can be discharged as electric current by connecting it to a load. Electrochemical storage systems store energy as chemical energy which can then be converted into electricity through chemical reactions. They include fuel cells, supercapacitors, and batteries.

Table 1 below compares the different energy storage technologies discussed above. It is noteworthy that batteries have a wider range of in all aspects of comparison. This is because there are very many types of batteries that are commercially available, with each type optimizable for different purposes and applications.

	Supercapacitor	Battery	Flywheel	SMES	Fuel Cell	Pumped Hydro	CAES
Charge Time	1-30 s	0.3-5h	0.5-2h	0.1-5h	0.3-5h	10-50h	1-50h
Reverse Time (S)	0.01	0.01	0.1	0.01	360	10	360
Energy Density (Wh/kG)	1-10	30-130	5-50	10-50	20-30	0.2-0.7	20-50
Power Density (W/kg)	10^3-10^5	10-10^2	10^2-10^4	10^3-10^4	10^2-10^3	Not relevant	Not relevant
Rated Power (MW)	0.01-5	0.01-90	0.1-10	1-50	0.01-90	500-5000	100-1000
Life Cycle	$>10^6$	10^3	10^4-10^6	$>10^6$	10^3	10^4-10^6	10^4-10^5
Efficiency	>95%	60-99%	85-90%	>95%	40-60%	70-85%	75-80%
Capital Cosst (£/kW)	300-500	300-3000	3000-5000	700-3000	700-3000	700-2000	700-1500
Cost/Cycle (¢/kWh)	2-20	9-100	3-20	6-100	6-100	0.1-1.5	2-5
Sitting Requirement	Close to load	Close to load	Close to load	Substations/ generators	Close to load	Geological consideration	Geographical consideration

Table 1: Energy Storage Technology Comparison [5-9]

Batteries are the main storage devices used in PV power systems. They are also used to operate PV systems near their maximum power points (MPP), to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. The two main classes of batteries are primary batteries and secondary batteries. Primary batteries cannot be recharged and are thus not applicable in PV systems. Examples include carbon-zinc and lithium batteries used in consumer electronics. Secondary batteries can be recharged and are thus used in PV systems. The most common battery types used with PV systems are lead-acid, lithium-ion, nickel-metal hydride, and nickel-cadmium.

1.1 Lead-Acid (Pb-acid) Batteries:

The positive electrode in a Pb-acid battery is composed of lead dioxide (PbO₂) while the negative electrode if composed of porous lead (Pb). The electrolyte is composed of 6 molar sulphuric acid (H₂SO₄).

During discharge the following reactions occur at the electrodes:
   a) Positive electrode: $PbO_2 + SO_4^{-2} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$
   b) Negative electrode: $PB + SO_4^{-2} \rightarrow PbSO_4 + 2e^-$
   c) Overall: $PB + PbO_2 + 2SO_4^{-2} + 4H^+ \rightarrow 2PbSO_4 + 2H_2O$

Reactions at the positive and negative electrodes lead to formation of lead sulphate coats around the electrodes which lead to reduction of the acid electrolyte. Since lead sulphate is a poor conductor, further reactions are limited; charging of the battery forces electrons to flow from the positive electrode to the negative electrode, reversing the 'sulphation' process [10].

The main advantages of lead acid batteries include: a) they are low cost as they benefit from maturity of technology, b) they are widely available and thus easy to find parts, and c) they handle abuse (overcharge or over-discharge) better than other batteries [10]. The main disadvantages are that they have shorter shelf-lives compared to emerging technologies and that they are more sensitive to temperatures compared to other brands [10]. They also suffer leakages which can lead to damage of the batteries [10].

1.2 Lithium-Ion (Li-Ion) Batteries:

The positive electrode in a Li-ion battery is composed of a lithiated form of a transition metal oxide, usually lithium cobalt oxide (LiCoO₂) or lithium manganese oxide (LiMn₂O₄) while the negative electrode is composed of carbon (c), usually graphite (C₆). The electrolyte is composed of solid lithium salt electrolytes (LiPF₆, LiBF₄, or LiClO₄) and organic solvents (ether).

During discharge, the following reactions occur at the electrodes, where $x = 1\ or\ 0$:
   a) Positive electrode: $LiCoO_2 \rightarrow Li_{1-x}CoO_2 + xLi^+ + xe^-$
   b) Negative electrode: $xLi^+ + xe^- + 6C \rightarrow Li_xC_6$
   c) Overall: $LiCoO_2 + C_6 \rightarrow Li_{1-x}CoO_2 + Li_xC_6$

During discharge, the cobalt Co is oxidized from Co^{3+} to Co^{4+} while the reverse (reduction) occurs during charging. Li-ion batteries do not accept well a high initial charging current. Also, cells in a battery pack need to be equalized to avoid falling below the minimum cell voltage of about 2.85V/cell. Therefore, Li-ion batteries need to be initially charged with a constant current profile, and thus the need of a charger. Typical float voltage is above 4V (usually 4.2V). Carbonaceous materials used in all Li-ion batteries lead to formation of a solid electrolyte interface (SEI) around the carbon electrodes, as a result of non-reversible chemical reactions between the carbon electrodes and lithium ions. As the SEI gets thicker, it leads to capacity decline and to eventual stoppage of the battery performance [11]. The lifetime and cyclability of Li-ion cell therefore depends on its SEI layer [11].

Advantages of Li-ion batteries include: a) they are lighter and smaller than lead acid batteries of similar capacities, b) they have longer shelf-lives (replacement every 5-7 years as opposed to 1.5-2 years with sealed lead acid), c) they can withstand up to 60°C without degradation and thus no need for air conditioning, d) they have faster recharge times 20-25% higher turnaround charge efficiency compared to Pb-acid batteries, e) they have more discharge cycles (5-10x), f) they have a full depth of discharge capability, g) they can be easily and remotely monitored, h) no servicing or watering required, i) no need for hydrogen gas extraction provisions, j) time between recharges is 26 weeks as opposed to 2 weeks for sealed lead acid, k) less cells in series needed to achieve some given voltage and, l) no deposits every charge/discharge cycle and thus 99% efficiency [12]. The main disadvantage of Li-ion batteries is that they are very expensive compared to other technologies.

1.3 Nickel-Metal Hydride (Ni-MH) Batteries:

The positive electrode of an Ni-MH battery is composed of nickel oxyhydroxide (NiO(OH)) while the negative electrode is composed of a metal hydrides such as AB2 (where A is titanium and/or vanadium, and B is zirconium or nickel, modified with chromium, cobalt, iron, and/or manganese) or AB5 (where A is a rare earth mixture of lanthanum, cerium, neodymium, and/or praseodymium, and B is nickel, cobalt, manganese, and/or aluminium). The electrolyte is composed of potassium hydroxide (KOH).

During discharge, the following chemical reactions occur at the electrodes:
   a) Positive electrode: $NiO(OH) + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$
   b) Negative electrode: $MH + OH^- \rightarrow M + H_2O + e^-$
   c) Overall: $NiO(OH) + MH \rightarrow Ni(OH)_2 + M$

The electrolyte is not affected because it does not participate in the reaction. Ni-MH batteries do not accept well a high initial charging current and are thus no suitable for charging with a constant-voltage method. Float voltage is about 1.4V while minimum voltage is about 1V.

Advantages of NI-MH batteries include the fact that they are less sensitive to high temperatures than Li-ion and Lead-acid batteries and that they can handle abuse (overcharge or over-discharge) better than Li-ion batteries. The main disadvantages are that more cells in series are needed to achieve some given voltage, compared to similarly sized Li-ion or Pb-acid batteries, and that they are very expensive.

1.4 Nickel-Cadmium (Ni-Cd) Batteries:

The positive electrode of a Ni-Cd battery is composed of nickel oxyhydroxide (NiO(OH)), same as with Ni-MH batteries, while the negative electrode is composed of cadmium. The electrolyte is composed of potassium hydroxide (KOH), same as in Ni-MH batteries.

During discharge, the following chemical reactions occur at the electrodes:
   a) Positive electrode: $2NiO(OH) + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$
   b) Negative electrode: $Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^-$
   c) Overall: $2NiO(OH) + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$

The electrolyte is not affected because it does not participate in the reaction. As with Ni-MH batteries, Ni-Cd batteries do not accept well a high initial charging current and are thus no suitable for charging with a constant-voltage method. Float voltage is about 1.4V while minimum voltage is about 1V.

The main advantage of Ni-Cd batteries is that they are less sensitive to high temperatures than all other batteries. Also, they handle abuse (overcharge or over-discharge) better that Li-ion. The main disadvantages are that more cells in series are needed to achieve some given voltage and that they are very expensive.

Table 2 below shows a comparison of different parameters of the four batteries discussed above.

	Lead-Acid	Ni-Cd	Ni-MH	Li-ion
Cell Voltage (V)	2	1.2	1.2	3.6
Specific Energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific Power (W/kg)	<300	150-300	<200	3-100
Energy density (kWh/m^3)	25-60	25	70-100	80-200
Power density (MW/m^3)	<0.6	0.125	1.5-4	0.4-2
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	> 1min	1 min -8 hr	> 1min	10 s – 1 hr
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75-90	75	81	99

Table 2: A Comparison of Different Types of Batteries [13,14]

1.5 Battery Bank:

A large connection (grouping) of batteries can be connected in series and/or parallel to increase voltage and/or current output for larger applications. Such a grouping is called a battery bank. Battery banks are used mainly with decentralized DC power generation systems, such as PV-based communal grids to provide electricity during islanded operations. They are also used to provide uninterrupted power supply to sensitive installations such as banks, data centres, hospitals, etc.

Available battery bank capacity at a time t(h) during charging and discharging are given by, respectively [15, 16]

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) + \left[P_{PV}(t) - \frac{P_L(t)}{\eta_{inv}}\right]\eta_{bat} \qquad (1)$$

$$C_{bat}(t) = C_{bat}(t-1)(1-\sigma) - \left[\frac{P_L(t)}{\eta_{inv}} - P_{PV}(t)\right] \tag{2}$$

where $C_{bat}(t)$ and $C_{bat}(t-1)$ are the available battery bank capacities (Wh) at times t and $t-1$, respectively, σ is the self-discharge rate of the battery bank, $P_{PV}(t)$ is the power generated by the PV system at time t, $P_L(t)$ is the load demand at time t, η_{inv} is the inverter efficiency, and η_{bat} is the battery charging/discharging efficiency.

Storage capacity of a battery bank is constrained by the following equation at any given time

$$C_{batmin} \leq C_{bat}(t) \leq C_{batmax} \tag{3}$$

where C_{batmin} and C_{batmax} are the minimum and maximum allowable storage capacities.

If we use the storage nominal capacity C_{batn} in place of C_{batmax} then

$$C_{batmin} = DOD \times C_{batn} \tag{4}$$

where DOD is the depth of discharge, maximum permissible depth of battery discharge.

1.6 Environmental Effects of Batteries:

Primary batteries are not rechargeable and are thus the most disposed in the world, with a typical person in USA throwing away about 8 batteries per year. The population of USA is over 380 million, and therefore over 3 billion batteries are disposed by individuals in USA every rear. These batteries contain materials such as lead, cadmium, mercury, copper, zinc, manganese, lithium or potassium which are harmful to both the environment and humans. Proper disposal of batteries is therefore an important consideration for both manufacturers and recycling organizations. Currently, the most commonly used means of battery disposal is landfills. However, this option is harmful to the environment as the harmful products leak into the soil and could render nearby locations agriculturally useless for many years. Moreover, the harmful chemicals could also find their ways into nearby streams which end up in lakes or oceans and thus eventually find their way to residential homes. Cadmium is easily taken up by plant roots and accumulates in fruits, vegetables, and grass, from where they are consumed by humans and animals. Prolonged intake of these harmful materials have negative effects on human lives including reduced IQ in children, abdominal pains, damage to liver and kidney, or even cancer, to name a few. Also, landfills generate methane gas which further contributes to global warming.

There are many options of dealing with batteries that have expired including:
  a) Recycling of used batteries: This is a better option that dumping of batteries in landfills because it saves natural resources, saves energy, reduces pollution, reduces the need for landfills, generates income, and reduces imports.
  b) Using of rechargeable secondary batteries more than primary batteries as the former have longer shelf-lives and thus less need for disposal. Moreover, they are more easily recycled that the latter due to their components.

c) Making collection of expired batteries easier and cost-effective by offering financial incentives to consumers who sell their expired batteries to collectors other than disposing of them unsafely.
d) Stricter regulation of battery disposal processes
e) More research and development into alternative energy storage techniques which are less harmful to the environment, such as fuel cells

2.0 Modelling and Simulations:

The main parameters used in modelling a battery are [17]:
a) Internal resistance: this is caused by charge and discharge conditions of a battery and increases as battery efficiency decreases
b) Self-discharge resistance: this is caused by electrolysis of water at high voltage levels and by leakage current at terminals when voltage levels are low
c) Charge and discharge resistances: these are due to electrolyte, plate, and fluid resistances
d) Polarization capacitance: this is caused by chemical diffusion that occurs within the electrolyte terminals
e) Terminal voltage: this is the voltage across the battery terminals and a load
f) Open circuit voltage: this is the voltage across battery terminals with no load

Equation of state of charge (SoC) of a battery is given by [18]

$$SoC = \propto SoC_c + (1-\propto)SoC_v \tag{5}$$

where $\propto$ ($\in [0,1]$) is the weight factor, SoC_c is the current-based state of charge, and SoC_v is the voltage-based state of charge.

SoC is a function of time and can thus alternatively be expressed as

$$SoC_c(t) = SoC_c(0) - \frac{1}{Q}\int_0^t I(t)dt \tag{6}$$

where Q is the battery capacity in (Ah), and relates the battery current I to SoC.

Many battery models have been developed for different applications. Electrochemical models describe a battery using a set of six coupled differential equations. These models are used in battery designs. Electric circuit models are mainly used in electrical engineering to study the electrical properties of batteries.

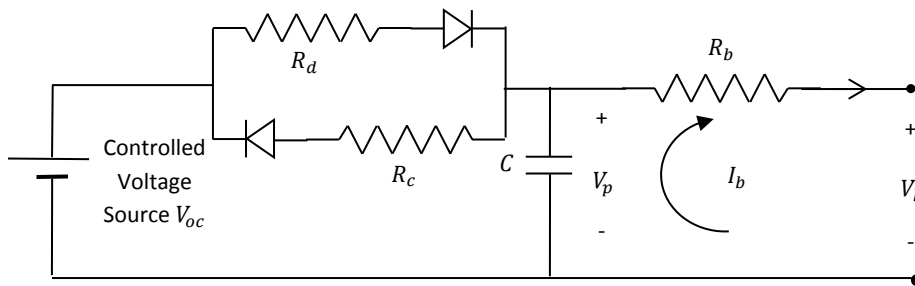Figure 1 shows a circuit model of a battery.
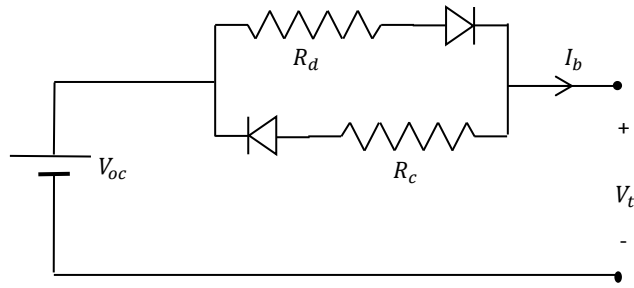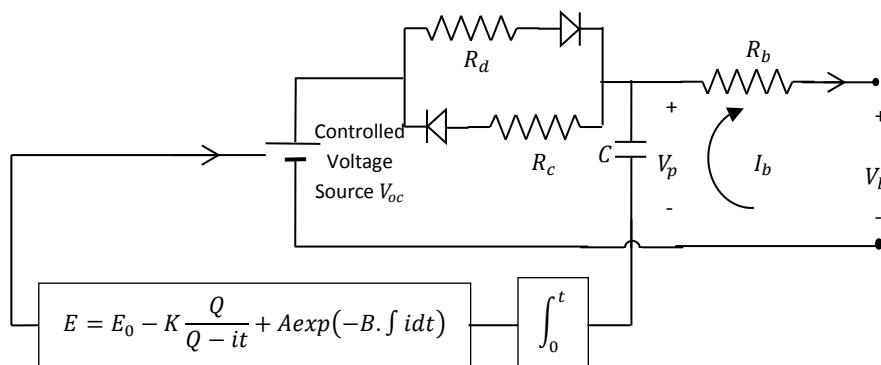
Fig. 1: Circuit Model of a Battery

R_d and R_c represent internal resistances which are on or off during discharging and charging, respectively; during charging and discharging, one diode conducts while the other is reverse biased. Parameters of the two internal resistances account for the loss in energy, electrical or non-electrical. It is noteworthy that the two diodes are just for modelling purposes and are thus not physically implanted in battery structures.

To simulate chemical diffusion of electrolytes and the resultant effect of causing transient currents within the battery, a capacitor is added to the model as shown in figure 2 [19]

Fig. 2: Circuit Model of a Battery with Capacitor

A proportional feedback loop controller can be added to the above model, as shown in figure 3 to provide the model with a voltage source that is controlled and in series with a resistance. This enables the model to simulate a charge and a discharge process with the controlled voltage based on the SOC of the battery [19].

Fig. 3: Circuit Model of a Battery with Feedback Loop

The controlled voltage source is described by the following equation [19]

$$E = E_0 - K\frac{Q}{Q - it} + Aexp(-B \cdot \int idt) \tag{7}$$

where E is the no-load voltage (V), E_0 is the battery constant voltage (V), K is the polarization (V) voltage, Q is the maximum battery capacity (Ah), $\int idt$ is the actual battery charge (Ah), A is the exponential zone amplitude (V), and B is the exponential zone time constant inverse $(Ah)^{-1}$.

2.1 Charging State ($V_p \leq V_{oc}$; $i^* < 0$):

During charging, the feedback loop controller compares the difference in SOC and some predefined values of SOC to determine whether the battery has reached the lowest specified value of SOC. If the lowest set value is reached, the DC machine begins to charge the battery at a pre-set charge current. This process is described by equations 8, 9, and 10 for sealed Pb-acid, Li-ion, and Ni-MH and Ni-Cd batteries, respectively [18,20]:

$$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s}\right) \tag{8}$$

$$f_1(it, i^*, i) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot exp(-B \cdot it) \tag{9}$$

$$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{|it| + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s}\right) \tag{10}$$

where it is extracted capacity (Ah), i is battery current (A), i^* is the low frequency current dynamics (A), $Exp(s)$ is the exponential zone dynamics (V), $Sel(s)$ represents the battery mode and equals 1 during charging and 0 during discharge,

### 2.2 Discharging State ($V_p \geq V_{oc}$; $i^* > 0$):

During discharge, the feedback loop controller measures the difference in SOC and some predefined SOC values to determine whether a pre-set maximum value of SOC has been reached. . This process is described by the following set of equations for sealed Pb-acid, Li-ion, and Ni-MH and Ni-Cd, respectively [18,20]:

$$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot 0\right) \tag{11}$$

$$f_2(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot exp(-B \cdot it) \tag{12}$$

$$f_2(it, i^*, i, Exp) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + Laplace^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot 0\right) \tag{13}$$

The above equations for charging and discharging states can be incorporated into the battery circuit model to give the model shown in figure 4.
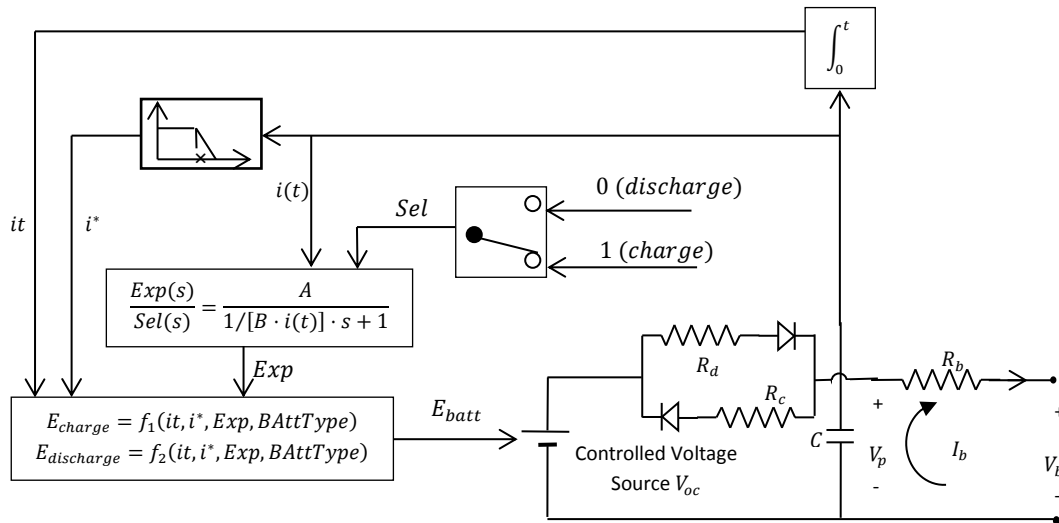
Fig. 4: Advanced Circuit Model of a Battery

The following assumptions are made in the model:
- Internal resistance is assumed to be constant during charging and discharging
- Parameters for the model are based upon values found from discharging and charging cycles
- There is change in capacity of the battery or in the amplitude of the current
- Temperature of the battery is not taken into consideration; a study has shown that there is a 50% loss in battery life for every 15°F above the standard 77°F cell temperature [21]
- Self-discharging state is not represented
- Battery is deemed to have no effect on the stored memory

The generic Simulink model shown in figure 5 is used to implement the circuit model of figure 4. The mask labelled 'Battery' implements a generic battery that models sealed Pb-acid, Li-ion, Ni-MH, and NI-Cd batteries. The type of the battery to be modelled is selected under parameters of the mask. A particular battery type's parameters are automatically loaded when it is selected in the mask. These parameters cannot be modified and are based on manufactures' data sheets. In the mask parameter tab, nominal voltage (V) represents the end of the linear zone of the discharge characteristics while rated capacity (Ah) is the minimum effective capacity of the battery. The initial state of charge is set at 100%. The mask labelled the DC Machine charges the battery at a constant charge current. It is turned on if a pre-set minimum value of SOC is reached. The feedback loop controller takes measurements of SOC at different intervals and compares them to pre-defined values of SOC upper and lower limits. If the upper limit is reached, charging stops while if the lower limit is reached, charging begins. The feedback loop controller therefore determines when to charge the battery via the DC machine. The data output is fed into a scope and the simulation output feeds to workspace where obtained voltage, SOC, DC motor speed, and armature current are recorded.
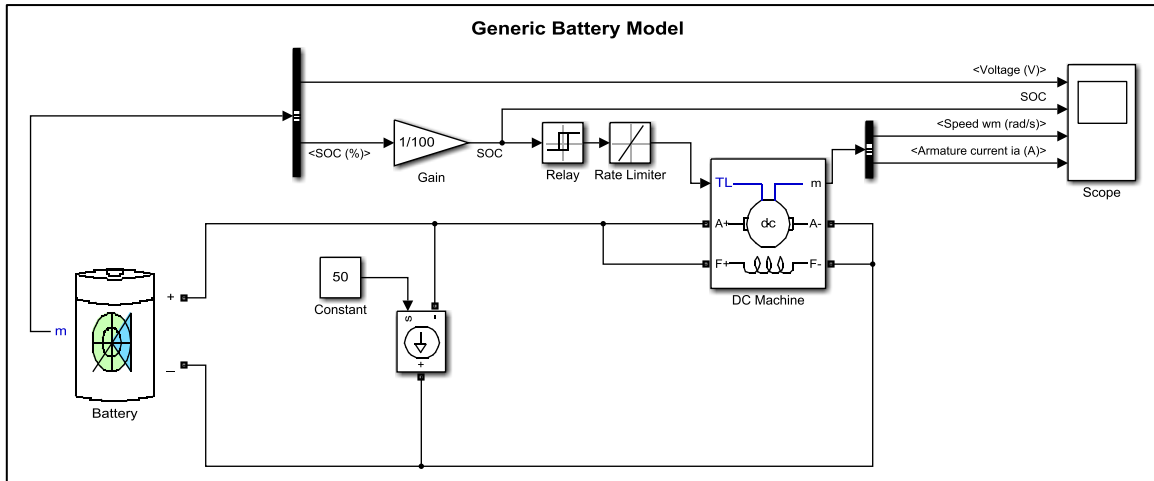
Fig. 5: Simulink Model of a Battery

3.0 Results and Discussion:

3.1 Sealed Pb-Acid Battery:

The following parameters were used for the Pb-acid battery: Nominal voltage = 12V; internal resistance = 0.0008 Ohms; nominal discharge current = 30A; nominal capacity (B) $(Ah)^{-1}$ = 46.54; rated capacity (Ah) = 150; and initial state-of-charge = 100%. Figure 6 shows plots of battery voltage and state of charge with time. Initially the state of charge is 1 (100%) and the battery voltage is at 12 V. The battery then begins to discharge with time. When the SOC reaches 0.4, the feedback loop controller instructs the DC machine to start charging the battery. This continues until SOC reaches 0.8 when charging stops and discharging process begins again. This cycle is repeated for the duration of simulation. Pb-acid batteries have optimum voltage window and lifetime in the 0.4 to 0.8 SOC range. This simulation results therefore validates the model.
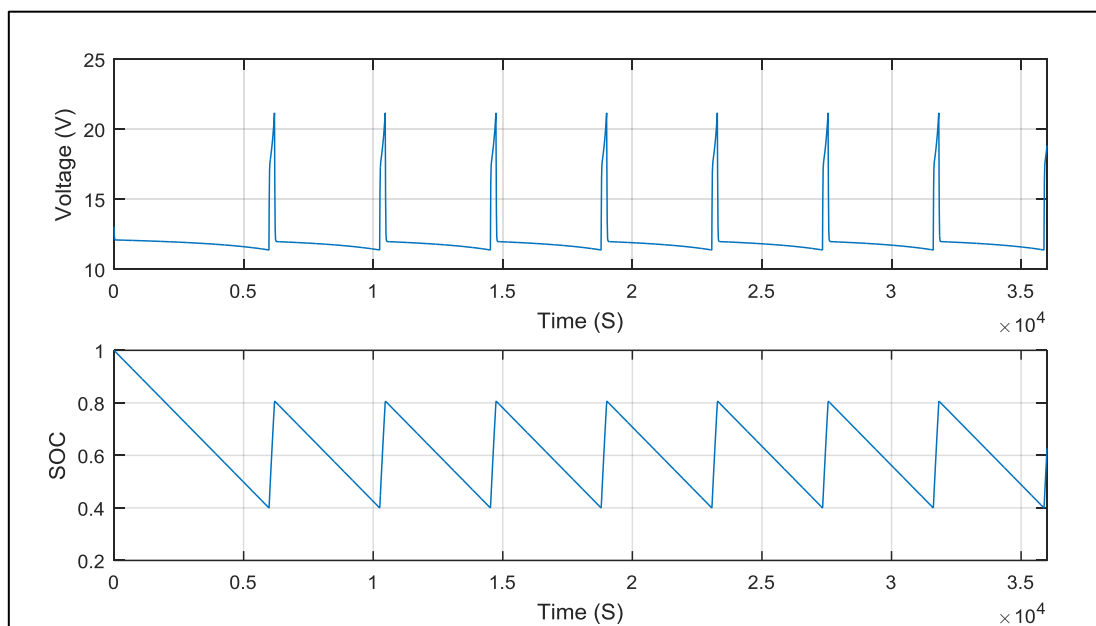

Fig. 6: Discharging/Charging Cycles of a Pb-Acid Battery

Depth of discharge (DOD) of a battery refers to the lowest permissible SOC. Deep cycle and large batteries can withstand up to 80% DOD (20% SOC). A battery's life is directly dependent on its DOD and charging/discharging cycles it experiences over its lifetime. Figure 7 shows a plot of voltage discharge rate and of DOD. It takes about 6,000 seconds (100 minutes) for the battery to discharge to minimum SOC and for the charging process to begin. The rate at which a battery is discharged affects its capacity and lifetime [22]; if discharging occurs too quickly, a battery's capacity is significantly diminished while if discharging occurs too slowly, the capacity is enhanced.
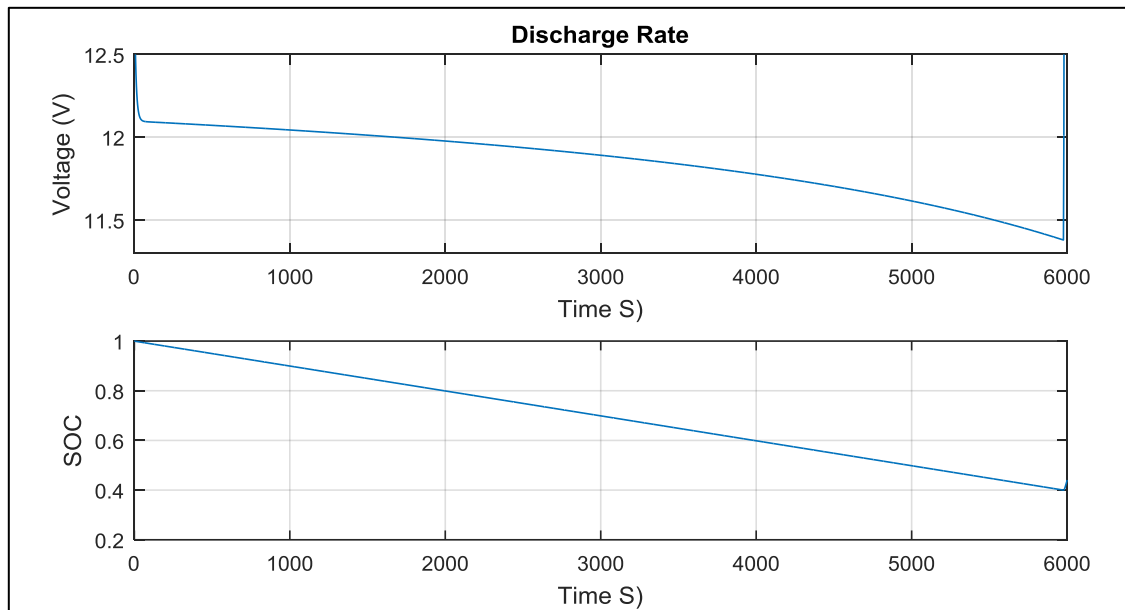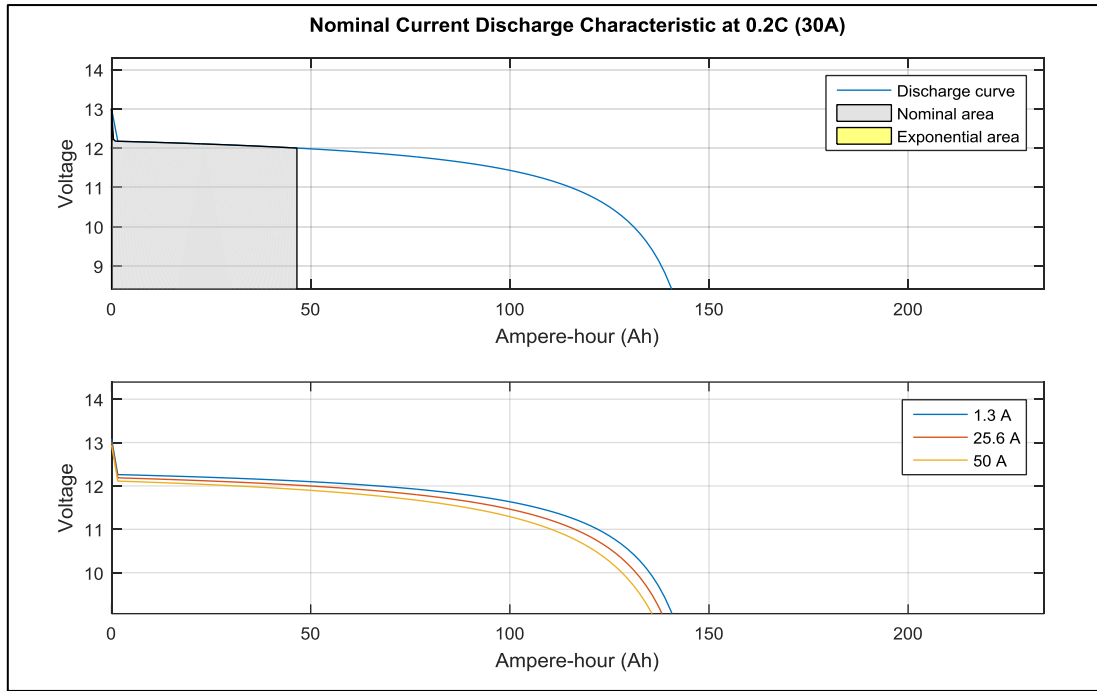

Fig. 7: Discharging Rate of a Pb-Acid Battery

Battery capacity is a function of time and rate of its discharge; a battery's capacity decreases as its discharge rate increases, a phenomenon called Peukert effect [22]. According to this law, the capacity of a battery can be found by plotting the discharge rate. Peukert's effect is given by [22]

$$C = I^K t \tag{14}$$

Where C is the battery capacity at 1A discharge rate, I is the discharge current, K is Peukert coefficient (typically between 1.1 and 1.3), and t is time.

Figure 8 shows effects of discharging current on nominal voltage; the voltage is significantly affected by the rate of discharge with lower discharge currents leading to slower discharge rates while higher discharge currents lead to faster discharge rates.

Fig. 8: Effects of Discharging Current on Rate of Discharge of a Pb-Acid Battery
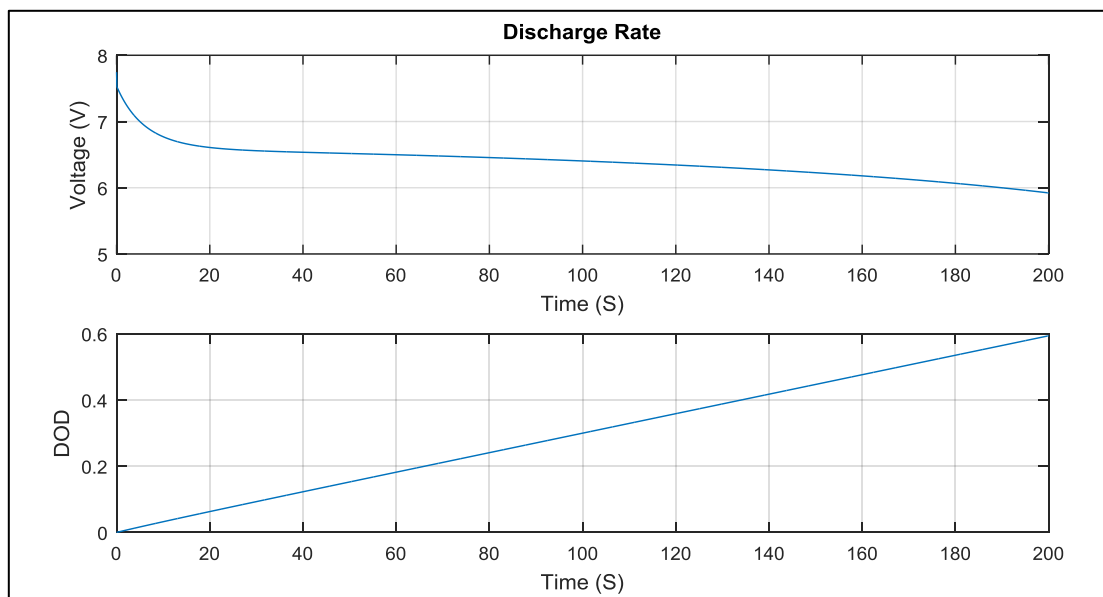
3.2 Li-Ion Battery:

The following parameters were used for the Li-ion battery: Nominal voltage = 7.2V; internal resistance = 0.0133 Ohms; nominal discharge current = 2.35A; nominal capacity (B) $(Ah)^{-1}$ = 4.88; maximum capacity (Ah) = 5.4; and initial state of charge = 100.

Figure 9 shows plots of battery voltage and state of charge with time. Initially the state of charge is 1 (100%) and the battery voltage is at 7.2 V. The battery then begins to discharge with time. When the SOC reaches 0.4, the feedback loop controller instructs the DC machine to start charging the battery. This continues until SOC reaches 0.9 when charging stops and discharging process begins again. This cycle is repeated for the duration of simulation; Li-ion batteries have a large SOC range than those of Pb-acid batteries.
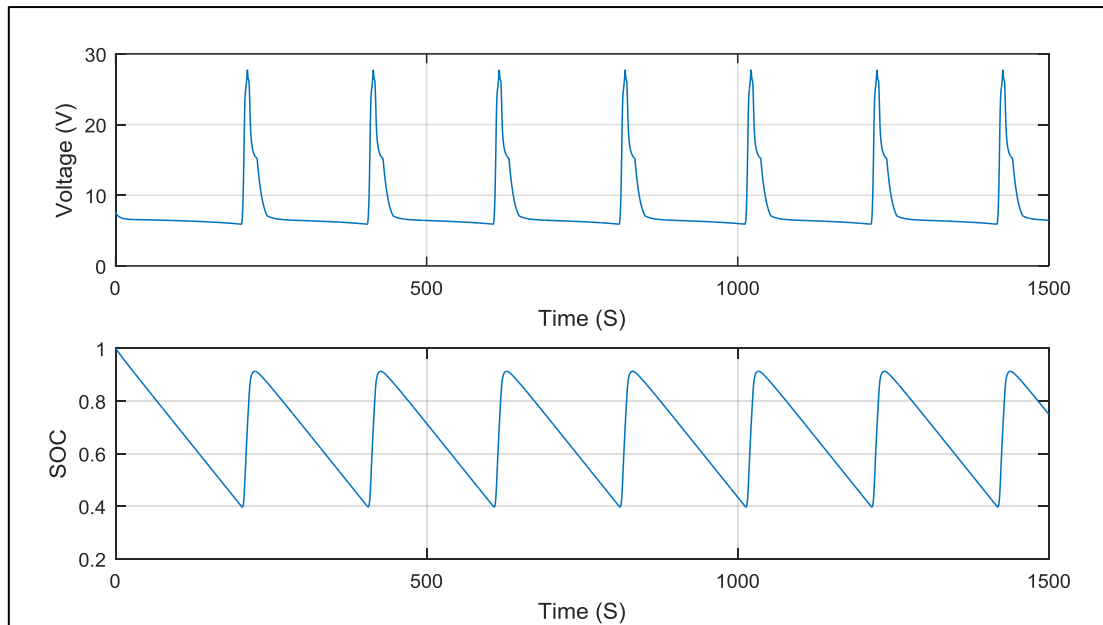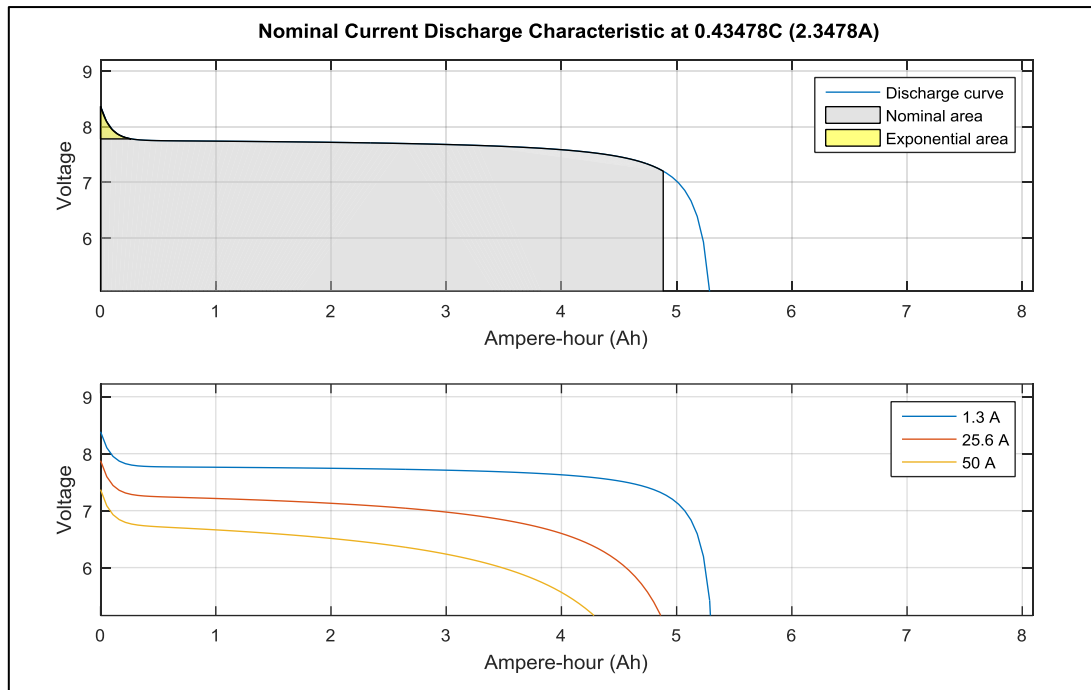
Fig. 9: Discharging/Charging Cycles of a Li-Ion Battery

Figure 10 shows a plot of voltage discharge rate and of DOD. It takes about 200 seconds for the battery to discharge to minimum SOC and for the charging process to begin. This is a smaller capacity battery and thus the faster charging/discharge rate.

Fig. 10: Discharging Rate of a Li-Ion Battery

Figure 11 shows effects of discharging current on nominal voltage; as with Pb-acid battery, the voltage is significantly affected by the rate of discharge with lower discharge currents leading to slower discharge rates while higher discharge currents lead to faster discharge rates. The nominal area of a Li-Ion battery is much larger than that of a Pb-acid battery, indicating better performance.

Fig. 11: Effects of Discharging Current on Rate of Discharge of a Li-Ion Battery

3.3 Ni-MH Battery:

The following parameters were used for the Ni-MH battery: Nominal voltage = 200V; internal resistance = 0.30769 Ohms; nominal discharge current = 1.3A; nominal capacity (B) $(Ah)^{-1}$ = 6.5; initial state of charge = 100%; and maximum capacity (Ah) = 7.

Figure 12 shows plots of battery voltage and state of charge with time. Initially the state of charge is 1 (100%) and the battery voltage is at 200 V. The battery then begins to discharge with time. When the SOC reaches 0.4, the feedback loop controller instructs the DC machine to start charging the battery. This continues until SOC reaches 0.8 when charging stops and discharging process begins again. This cycle is repeated for the duration of simulation; Ni-MH batteries have a SOC range similar to that of Pb-acid batteries.
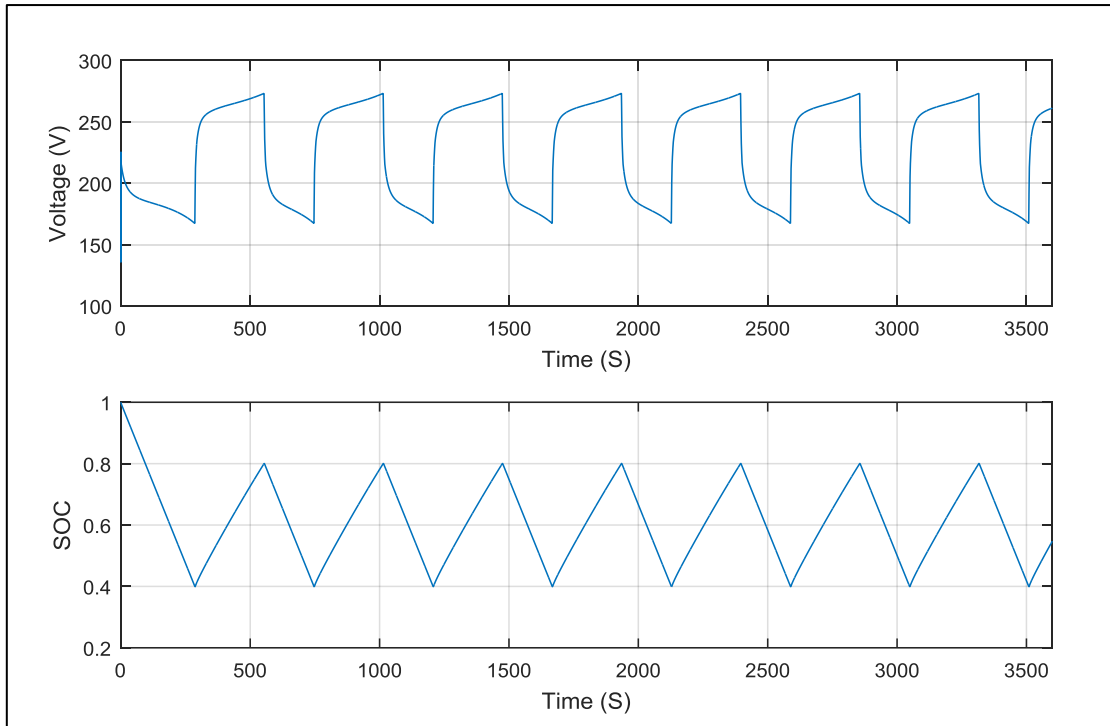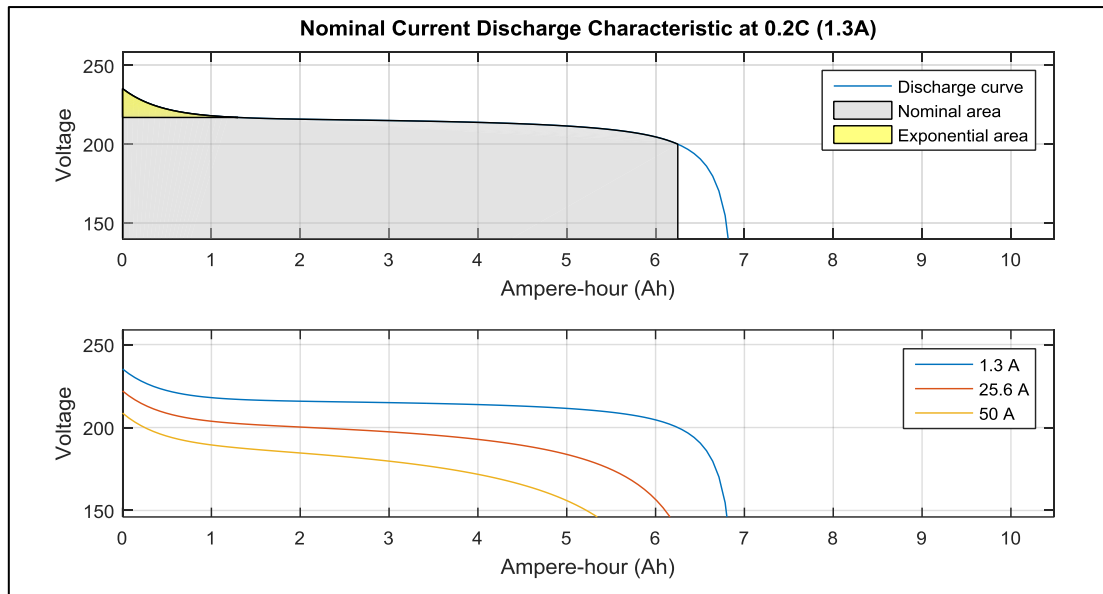
Fig. 12: Discharging/Charging Cycles of a Ni-MH Battery

Figure 13 shows a plot of voltage discharge rate and of DOD. It takes about 285 seconds for the battery to discharge to minimum SOC and for the charging process to begin.
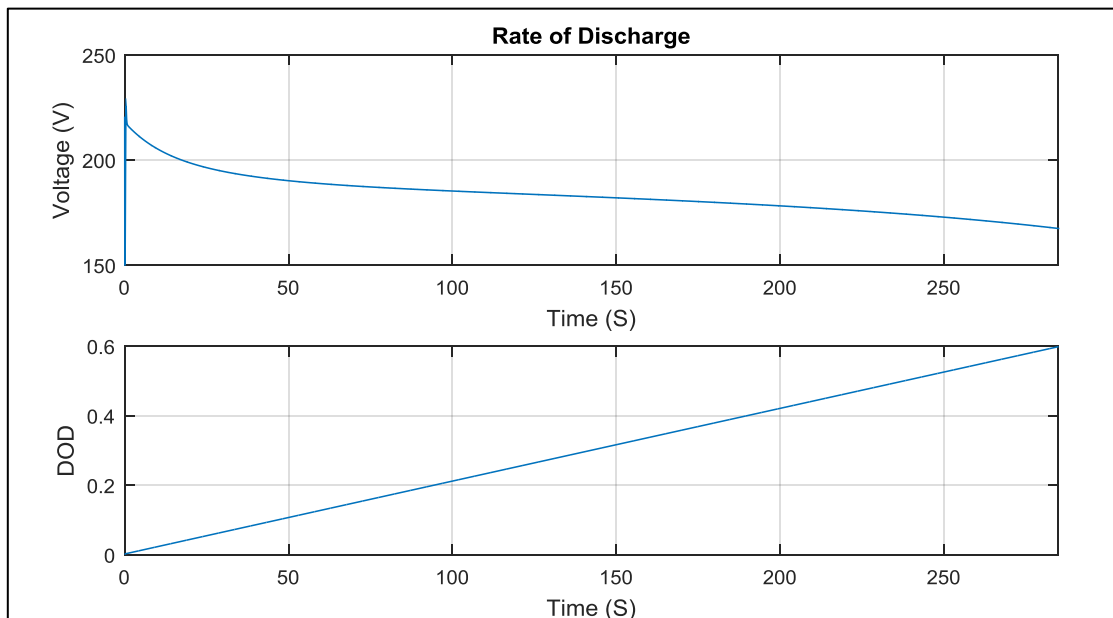
Fig. 13: Discharging Rate of a Ni-MH Battery

Figure 14 shows effects of discharging current on nominal voltage; as with Pb-acid and Li-ion batteries, the voltage is significantly affected by the rate of discharge, with lower discharge currents leading to slower discharge rates while higher discharge currents lead to faster discharge rates.

Fig. 14: Effects of Discharging Current on Rate of Discharge of a Ni-MH Battery

3.4 Ni-Cd Battery:

The following parameters were used for the Ni-Cd battery: Nominal voltage = 200V; internal resistance = 0.30769 Ohms; nominal discharge current = 1.3A; nominal capacity (B) $(Ah)^{-1}$ = 6.5; initial state of charge = 100%; and maximum capacity (Ah) = 7.

Figure 15 below shows plots of battery voltage and state of charge with time. Initially the state of charge is 1 (100%) and the battery voltage is at 200 V.
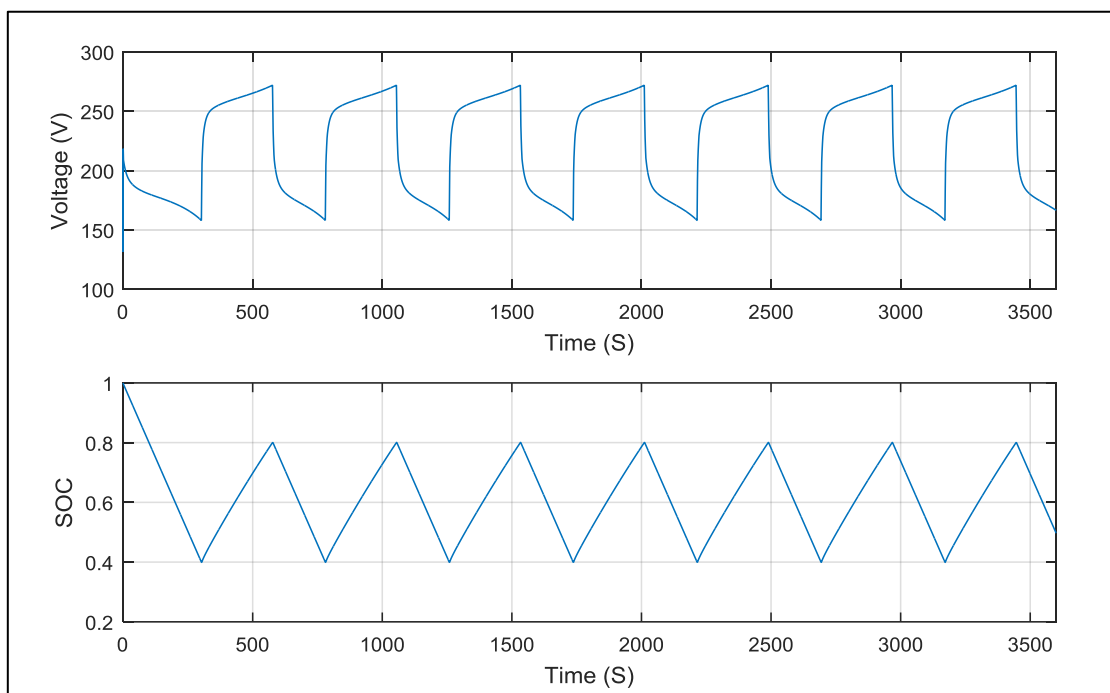
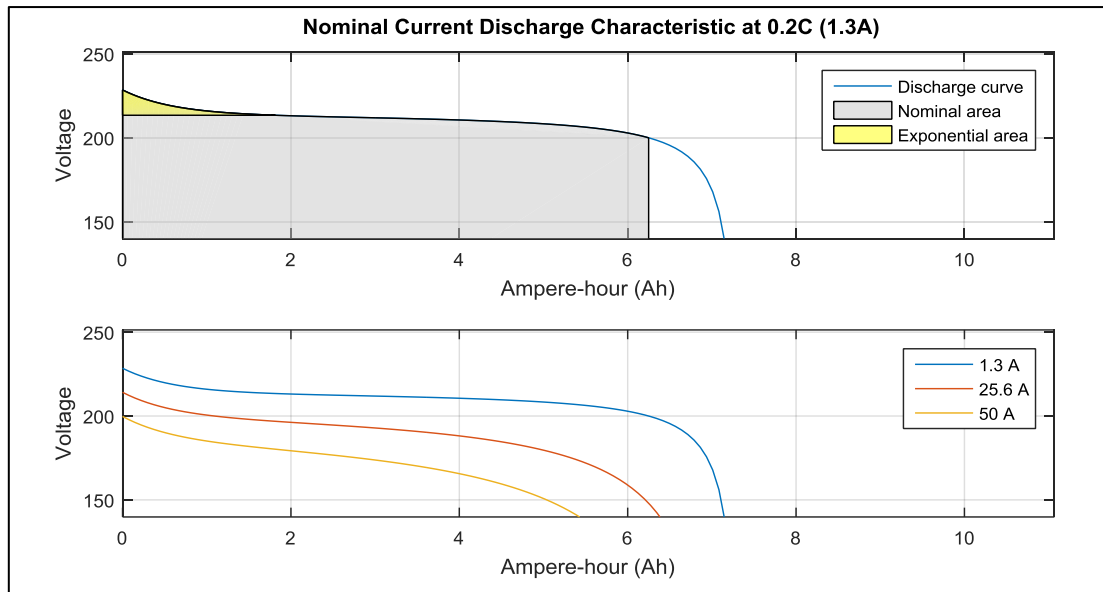**Fig. 15: Discharging/Charging Cycles of a Ni-Cd Battery**

The battery then begins to discharge with time. When the SOC reaches 0.4, the feedback loop controller instructs the DC machine to start charging the battery. This continues until SOC reaches 0.8 when charging stops and discharging process begins again. This cycle is repeated for the duration of simulation; Ni-Cd batteries are quite similar to Ni-MH batteries and also have a SOC range similar to that of Pb-acid batteries.

Figure 16 shows a plot of voltage discharge rate and of DOD. As with the Ni-MH battery, it takes about 285 seconds for the battery to discharge to minimum SOC and for the charging process to begin.
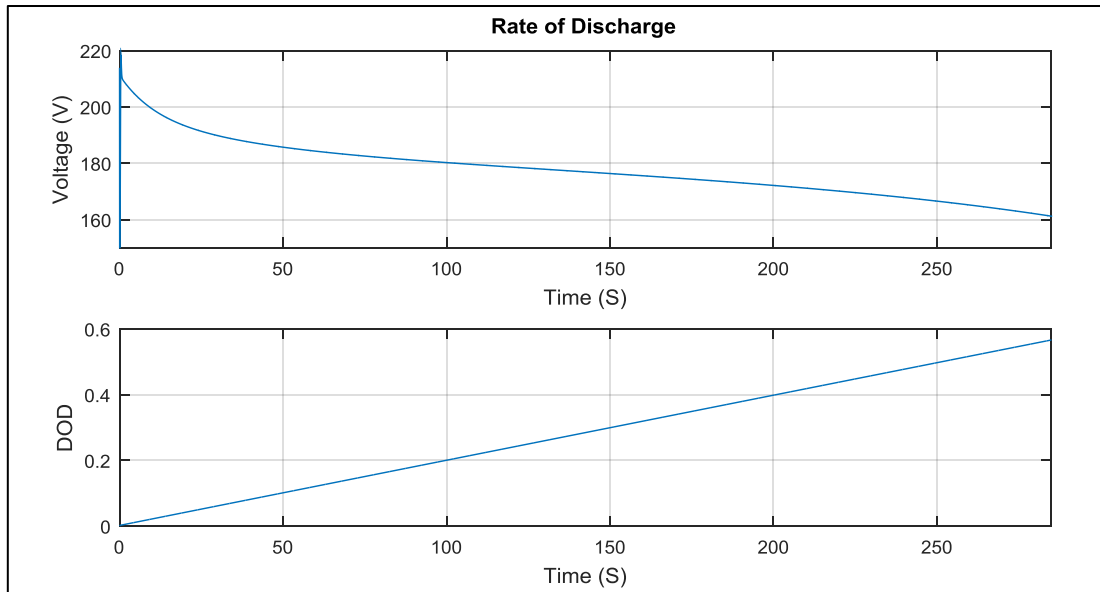
Fig. 16: Discharging Rate of a Ni-Cd Battery

Figure 17 shows effects of discharging current on nominal voltage. As with Pb-acid, Li-ion, and Ni-MH batteries, the voltage is significantly affected by the rate of discharge with lower discharge currents leading to slower discharge rates while higher discharge currents lead to faster discharge rates.

Fig. 17: Effects of Discharging Current on Rate of Discharge of a Ni-Cd Battery

4.0 Conclusion:

In this paper energy storage technologies for PV systems have been reviewed, with a focus on batteries. Batteries are essential for islanded PV systems operations and for stability in grid-connected PV systems. The merits and demerits of different battery technologies are discussed. Environmental impacts of batteries are also reviewed. Four most common battery technologies used with PV systems, i.e., sealed Pb-acid, Li-ion, Ni-MH, and Ni-Cd have been modelled and simulated in Matlab/Simulink. Results show that Li-ion batteries have faster charging/discharging rates and with higher efficiencies.

References:

1. Jewell, W., Hu, Z., *The Role of Energy Storage in Transmission and Distribution Efficiency*, Transmission and Distribution Conference and Exposition (T&D), IEEE PES, 1–4, 2012
2. Manz, D., Piwko, R., Miller, N., Look Before *You Leap: The Role of Energy Storage in the Grid*, Power Energy Mag. IEEE **10**: 75– 84, 2012
3. Jiang, Q., Wang, H., *Two-Time-Scale Coordination Control for a Battery Energy Storage System to Mitigate Wind Power Fluctuations*, Energy Conversion, IEEE Trans. **28**: 52–61, 2013
4. Roberts, B., Sandberg, C., The *Role of Energy Storage in Development of Smart Grids*, Proc. IEEE **99**: 1139–1144, 2011
5. Hadjipaschalis, I., Poullikkas, A., Efthimiou, V., *Overview of Current and Future Energy Storage Technologies for Electric Power Applications*, Renew. Sustain. Energy Rev. **13**: 1513–1522, 2009

6. Roberts, B., McDowall, J., *Commercial Successes in Power Storage*, Power Energy Mag. IEEE **3**: 24–30, 2005

7. Ter-Gazarian, A., *Energy Storage for Power System*, First Edition, the Institute of Engineering and Technology, London, United Kingdom, 1994

8. Lindley, D., *Smart Grids: The Energy Storage Problem*, Nature **463**: 18–20, 2010

9. Electricity Storage Association, Electricity Storage, http://www.electricitystorage.org/

10. Wahl, K., *A Short History of Electrochemistry*, Galvanotechnik **96**: 1820–1828, 2005

11. Gnanaraj, J. S., Thompson, R. W., Iaconatti, S. N., et al., *Formation and Growth of Surface Films on Graphitic Anode Materials for Li-Ion Batteries,* Electrochemical and Solid-State Letters **8**: A128–A132, 2005

12. Teofilo, V., Merritt, L., Hollandsworth, R., *Advanced Lithium Ion Battery Charger*, *IEEE Aerospace and Electronic Systems Magazine 12: 30-36, 1997*

13. Tremblay, O., Dessaint, L. A., Dekkiche, A. I., *A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles*, Vehicle Power and Propulsion Conference (VPPC 2007), 284-289, 2007

14. Chiasson, J., Vairamohan, B., *Estimating the State of Charge of a Battery*, Control Systems Technology, IEEE Transactions on , **13**: 465- 470, 2005

15. Bogdan, S. B., Salameh, Z. M., *Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System*, IEEE Transactions on Energy Conv. **11**: 367-375, 1996

16. Bin, A., Hongxing, Y., Shen, H., et al., *Computer Aided Design for PV/Wind Hybrid System, Renewable Energy* **28**: 1491-1512, 2003

17. Tyagi, M., *Introduction to Semiconductor Materials and Devices*, John Wiley & Sons, Hoboken, NJ, 1991

18. Xiao, B., *A Universal State-of-Charge Algorithm for Batteries*, DAC 687–692, 2010.

19. Tremblay, O., Dessaint, L.-A. *Experimental Validation of a Battery Dynamic Model for EV Applications,* World Electric Vehicle Journal, 2009

20. Solar Energy International. *Photovoltaics Design and Installation Manual.* 4th ed. British Columbia, New Society Publishers, 2004.

21. Chen, M., Gabriel, A., *Accurate Electrical Battery Model Capable of* Predicting *Runtime and I–V Performance*, IEEE Transactions on Energy Conversion **21** (2), 2006

22. Baert, D., Vervaet, A., *Lead-acid Battery Model for the Derivation of Peukert's Law,* Electrochimica Acta **44** (20), 1999