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Residential Battery Energy Storage Systems (BESS) Modeling and Effect on the Smart Grid from the Classroom Point of View

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Residential Battery Energy Storage Systems (BESS) Modeling and its Effect on the Smart Grid: A Classroom Point of View

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Introduction

Energy Storage Systems (ESS) technologies have existed for quite a long time and are becoming of paramount importance in the 21st century due to the smart grid. Recently, slowly the concept of electric generation has been shifting from the use of non-renewable energy sources (coal, oil etc.) to renewable sources (wind, tidal, solar, geothermal etc.). Due to the penetration of renewable energy sources into the present day power systems, the use of energy storage systems in power system management is growing. The evolution of the concept of energy storage systems undoubtedly offers new opportunities, challenges, and numerous advantages. Over the past few decades, many new advances have been made in this field of energy storage systems. These energy storage systems help overcome some of the limitations of electricity generation from renewable energy sources (the major one being intermittent nature of generation). Besides, they also offer a number of advantages like frequency regulation, transient stability, voltage support, flicker compensation, spinning reserve, uninterruptable power supply, load leveling, and peak shaving among others. Utilization of energy storage systems begins at the transmission level where large scale storage devices are the best options to be used. Next, the small scale energy storage devices are the ones that are used at the consumers end.

Small scale energy storage devices include battery energy storage system (BESS), thermal energy storage (TESS), ultra-capacitors (EDLC), and flywheels. Among the listed small scale energy storage systems, Battery Energy Storage systems (BESS) is the most commonly used category of energy storage systems with the renewable energy sources. Battery Energy Storage Systems play a significant role in the integration of small scale renewable energy sources into the main power system network (a.k.a. smart grid). They can be seen as the distinct and most viable solution for small scale renewable energy integration due to their remarkable properties like high energy density, technology up-gradation, power density, discharge time, life cycle, response time, cost and efficiency etc.

This paper reviews the latest advances in energy storage devices as applied to "residential energy storage" in the State of California. Furthermore, the paper demonstrates the modeling and simulation of BESS, the importance of a well-designed BESS, the aggregate effect of stability, voltage regulation and frequency in the smart grid. The aim of this paper is to articulate how to introduce a two week module on BESS systems to our Electric Power System Curriculum, mostly at the senior level courses.

Curriculum

The study, analysis, and simulation of BESS can be added to any electrical power systems engineering curriculum. We have chosen to do it at the senior level in a power electronics course. We believe that it is a natural flow to transition from power electronics to energy storage using power electronics. For example the auto industry is about to embark in the development and deployment of a 48 VDC battery system for vehicles. The intent is to use buck converters to drop the voltage to 12 VDC to power a well-established technology that utilizes 12 VDC. This can be done not only because power electronics have become affordable, but also because from the economics point of view a 48 VDC battery system has become very feasible.

The module has the objective of designing a residential BESS system according to the case (example) indicated in this paper. Modeling with Simulink is required, following the simulation shown in this paper. Students are required to know Simulink previous to this project. Simulink is taught at the junior level in the "numerical analysis" course and the IEEE and HKN societies offer workshops on Matlab/Simulink every semester. BESS is not included in the curriculum yet, thus there is no data for us to use to assess this module's effectiveness in student learning, as soon as we teach this material, we will have more information and will be able to identify the effectiveness of this module.

Renewable Energy

Renewable Energy sources are sustainable and naturally replenished such as solar irradiation, wind, tidal waves, biomass, and geothermal heat.

According to figures provided by EIA (Energy Information Administration) in 2012 consumption from renewable resources in the United States amounts to about 9 quadrillion BTUs. Also about 12% of the total energy generated in the United States was from renewable sources in 2012. New renewables (small hydro, modern biomass, solar, wind, geothermal) account for another 3% share and are rapidly increasing [1]. In its new monthly forecast, EIA, reports that solar generation in the electric power sector is expected to grow even more, increasing 79% in 2013, and 49% in the year 2014 [2].

Wind is the most abundant source of domestic electricity in the United States. According to the figures provided by NRDC (Natural Resources Defense Council), more than 11 million homes get their energy from wind power. There are more than 400 wind related manufacturing facilities in the United States[3].

Solar energy is converted directly into electricity by the use of Photovoltaic System. *32 Mega-watt Long Island Solar Farm* at *Brookhaven National Lab,* is the largest solar farm on the East Coast that produces electricity enough to provide power to approximately 4500 homes annually[4].

California is the leading nation in the United States in terms of solar power (PV) and also leads in the total number of homes with installed solar panels [5, 6]. California's largest operating photovoltaic power plant (Avenal Solar Facility) has 57.7 MW of installed capacity. According to the latest data update, California leads the nation in PV solar plants with the following numbers given by Edison [5] (*as of December 11, 2013):*

Item	Amount
Number of solar projects	*194,000*
Megawatts installed	*1,907*
Average cost/KW (<10KW)	*$5.92*
Average cost/KW (>10KW)	*$5.50*

As an example of a solar project we use the “Long Island Solar Farm (LISF) [4] “ that was developed by the Department of Energy in collaboration with Brookhaven National Laboratory. The project peak capacity is 32 MW with Crystalline Solar PV modules (164,312 panels). The annual energy output is estimated to be about 44 GWh with the potential to supply energy to 4500 homes.

Battery Energy Storage System – State of the Art Technology

State of art the technology of Battery Energy Storage Systems defines the development and knowledge achieved to date in the technology of battery energy storage systems. Today there are numerous types of Battery Energy Storage Systems used in integration with renewable energy sources such as solar and wind. These types of Energy Storage Systems are shown in Figure 1.

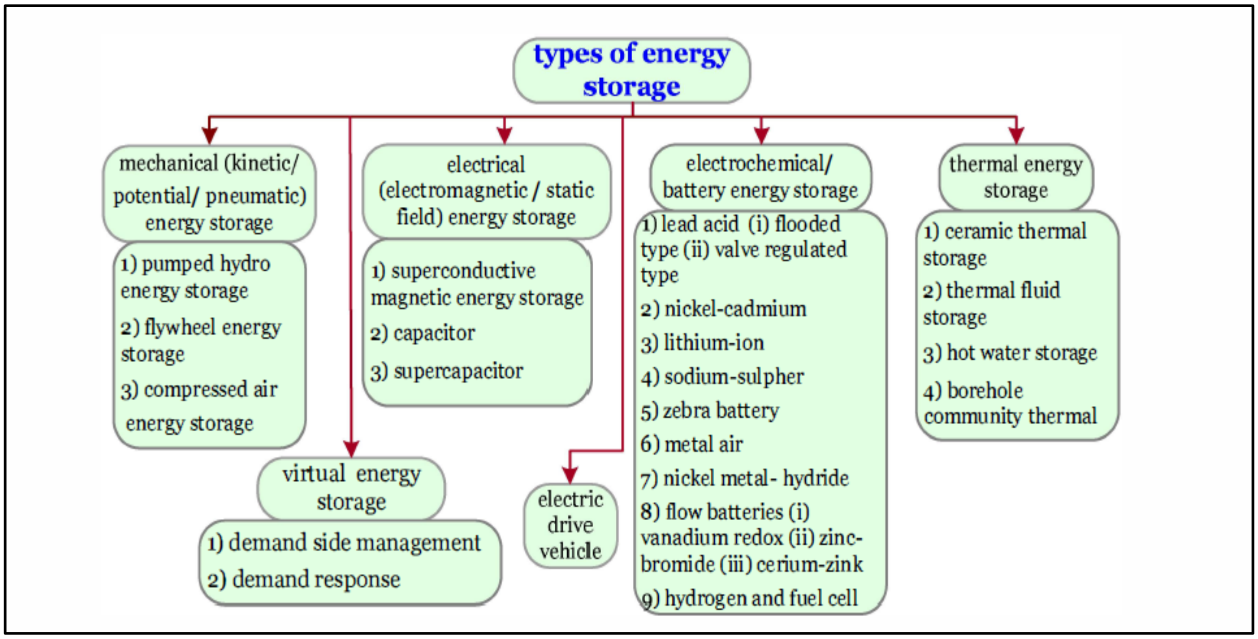


Figure 1: Types of energy storage systems (ESS) [7]

Electrochemical or Battery Energy Storage Systems (BESS)

We focus on Li-Ion and Lead Acid batteries, since they are the most widely utilized ones in residential applications.

1. Lithium-Ion (Li-ion)

Operating Principle- Lithium Ions (Li^+) are exchanged between the positive and negative electrodes. Positive electrode of Li-ion batteries is made from lithiated metal dioxide and negative electrode is made from graphite. An active material called *'liquid electrolyte'* is placed between the electrodes, which allows for the exchange of lithium ions during both the charge and discharge processes. The liquid electrolyte is normally a micro porous polyethylene in Li-ion batteries while in gel-polymer Li-ion batteries gel-polymer electrolyte is present[8].

Lithium Ion batteries possess characteristics and features that make them useful for their operation in large scale ESS. Following are some of those characteristics:

High Specific Energy and Energy Density

Specific energy and energy density are two main parameters that are required for the use in large scale ESS. At the early stages of their use, these batteries were having an energy density in the order of *200 Wh/L*. However, later on it has continuously increased and in 2012 it was projected to be *725 Wh/L* due to major break-through in anode material [9].

Recent advances show that using Silicon instead of graphite allows for micron-sized pores that are able to contain more lithium. By doing this, the Li-ion batteries have been able to store up to 10 times more energy.

Long life time

Secondly, Li-ion is suited for large scale operation due to its potential to achieve a long lifetime. Current Li-ion technology under test in grid-connected systems indicates a life-cycle of 20 years at 60% depth of discharge (DOD) per day. In terms of life-cycle, at 100% DOD, the battery can operate over 6000 cycles [8, 10].

High Efficiency

Li-ion cells are 94% efficient over 100% DOD for new cells. Efficiencies of 98% have been found for small discharges in case the battery is close to full charge. 91% is the maximum efficiency drop owing to cells' age, which is much more efficient compared to other technologies.

Applicability features

High efficiency Li-ion batteries operate in more diverse types of pricing structure. They can be used *for power quality applications* like voltage support and improving efficiency of distribution lines because of their quick response. Also, they are used in back-up power like *spinning reserve.* Due to intermittent nature of power generation by renewable energy sources, Li-ion batteries are useful for *smoothing fluctuations* and they are used *for large scale storage systems.*

Lastly, Li-ion batteries are used for *large scale ESS as Li-ion batteries are sealed cells, which require little to no maintenance.*

2. Lead Acid

Among all the batteries used worldwide Lead acid batteries are the ones that have been on the market the longest time. Batteries >1MW and >1MWh are already in use. In the State of California we have a 10MW/40MWH, which is the largest in the country.

Lead acid batteries have been in use since 1800s with the most common application in automobiles. They are also used as a source of backup power, such as uninterruptable power supply systems, power quality management for control systems and switching components. They have the following properties: [15, 16]:

- *Nonlinear power output*
- *Their lifetime varies with off usage*
- *Discharge rate*
- *Number of deep discharge cycles.*
- *High degree of maturity*
- *High efficiency*
- *Lowest initial storage cost of all batteries*.

<u>*Mathematical Model*</u>

The lead acid battery charge and discharge state can be expressed as follows:

Discharge model: $(i^* > 0)$

$$F_1(it, i^*, i, Exp) - E_0 - K\frac{Q}{Q-it}it + laplace^{-1}\frac{Exp(s)}{sel(s)}0 \qquad (1)$$

Charge model:$(i^* < 0)$

$$F_1(it, i^*, i, Exp) - E_0 - K\frac{Q}{it+0.1Q}i^* - K\frac{Q}{Q-it}it + laplace^{-1}\frac{Exp(s)}{sel(s)}\frac{1}{s} \qquad (2)$$

Where:

E_0- - constant voltage (V)
$Exp(s)$- exponential zone dynamics
$sel(s)$- represents the battery mode. $sel(s)$ = 0 during discharge of battery and = 1 during charging of battery
K-polarization constant (Ah^{-1}) or polarization resistance (ohms)
i^* - low frequency current dynamics(A)
I -battery current (A)
it −extracted battery (Ah)
Q − maximum battery capacity (Ah)

Challenges in Battery Technology

The fundamental principle behind batteries lies in the reaction of electrochemical processes. The temperature change in a battery during charging and discharging must be controlled as it affects the life expectancy of the battery. A major concern is the batteries' *life cycle*. Owing to its use in power applications, a battery may have to undergo numerous charges and discharges multiple times a day. During a low depth of discharge (DOD), the life cycle remains unaffected. However, large DOD can result in degradation of battery life. High discharge rate can also cause damage to the batteries and reduce the reliability of the energy storage system.

Assessment of different technologies in terms of storage application and storage technology

Figure 2 shows the comparison of different battery energy storage systems in terms of applications and technology [7]. Li-ion and Lead acid have the smallest capacity compared to the rest of the technologies indicated. Consequently, these two types of technologies are widely used in residential BESS.

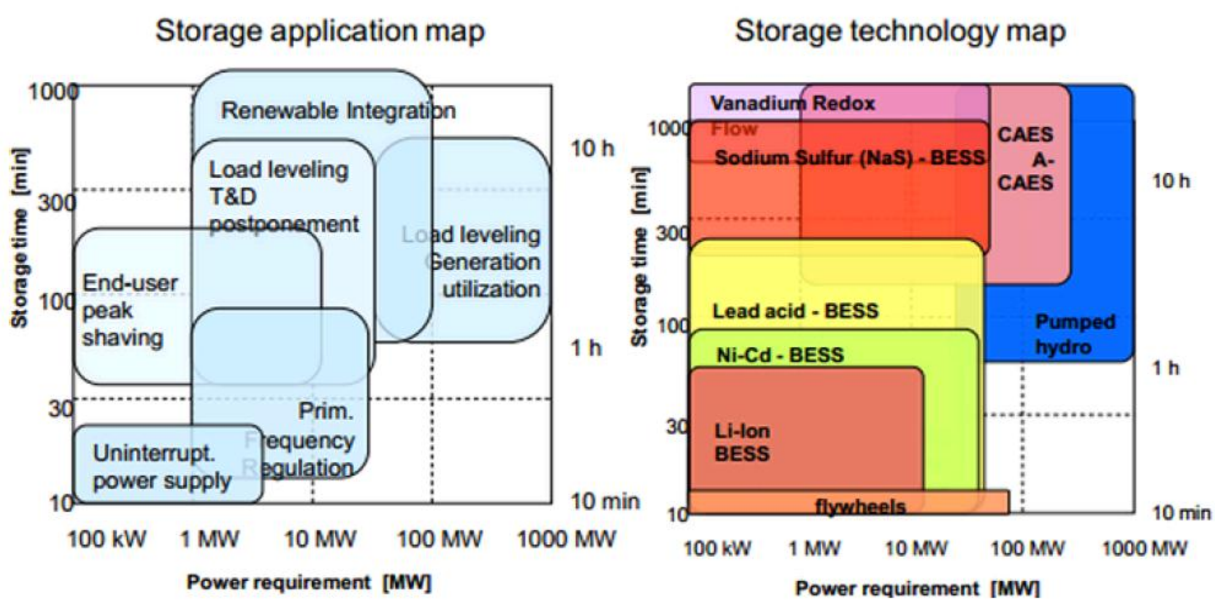


Figure 2: Storage Application & Storage Technology Map of Battery Energy Storage Systems

Example: Battery-Sizing for a Household[17]

Step 1: Battery Size - The size of battery is generally sized in ampere-hour (Ah) and the following equation is used to calculate the energy storage capacity:

$$C_b = \frac{\mathrm{E(d)}*N}{\mathrm{D\ (d)}*V} \qquad (3)$$

Where: C_b = Energy Storage Capacity
E (d) = Daily Energy Consumption (Wh)
D (d) = Maximum Allowable Depth of Discharge (DOD)
N = Number of days of storage required
V = Voltage of the battery system

Step 2: Determine number of Batteries N (b)

To calculate the number of batteries required, we take the ratio of ampere hour (Ah) of the system battery bank to the Ah for the battery voltage.

$$N(b) = \frac{\text{Amp−hour of the system battery bank}}{\text{Amp−hour of the battery voltage}} \qquad (4)$$

Step 3: Determine the amount of current delivery over a period of 1-hr using a 48VDC, 847.22 Ah storage bank.

$$I = \frac{\text{Amp−hour rating of battery storage}}{\text{period of hours charge}} \qquad (5)$$

Step 4: Determine the battery bank capacity in Watt-hour (Wh)

By oversizing the battery bank, the maximum hours of storage is determined as follows:
Maximum Hours of storage can be calculated using equation (6)

$$hours = \frac{\text{Storage Capacity of the battery (Ah)}}{\text{Discharge rate (A)}} \qquad (6)$$

In order to show the sizing of the battery system, let us consider the load profile of a single household as given below in Table 1.

TABLE 1: LOAD PROFILE OF A TYPICAL HOUSEHOLD

S No.	Appliances	Power Rating (W)	No. of Appliances	Hours of usage per day (h)	Daily energy Demand (Wh)	Monthly Energy Demand (kWh)
1	Microwave Oven	1100	1	0.25	275	8.25
2	CFL	30	3	6	540	16.2
3	Ceiling Fan	80	1	2	160	4.8
4	Laptop	50	1	0.5	25	0.75
5	Dishwasher	1250	1	1	1250	37.5
6	Air Conditioner	1000	1	6	6000	180
7	Coffee Maker	900	1	0.25	225	6.75
8	TV Flat Screen	100	1	4	400	12
9	**Total Power Required**	**4510**				
10	**Total Energy Required**				**8875**	**266.25**
11	**Total Energy with Battery Losses (x 1.25)**				**11093.75**	**332.81**
12	**Total energy with battery losses with ambient temp effect (x 1.1)**				**12203.13**	**366.09**
13	**Average Power Required**					
14	**Average Energy Required**					**12.20**

A typical Load Profile for a household is shown in Table 1 with the following key data to be used in further calculations:

1. Daily Energy Demand with Losses – 12.20 kWh/ day
2. No. of Load Appliances – 10
3. Total Power Required – 4.5 kW
4. Hours usage per day – 20 hours
5. Depth of Discharge (DOD) – 80% (0.80)

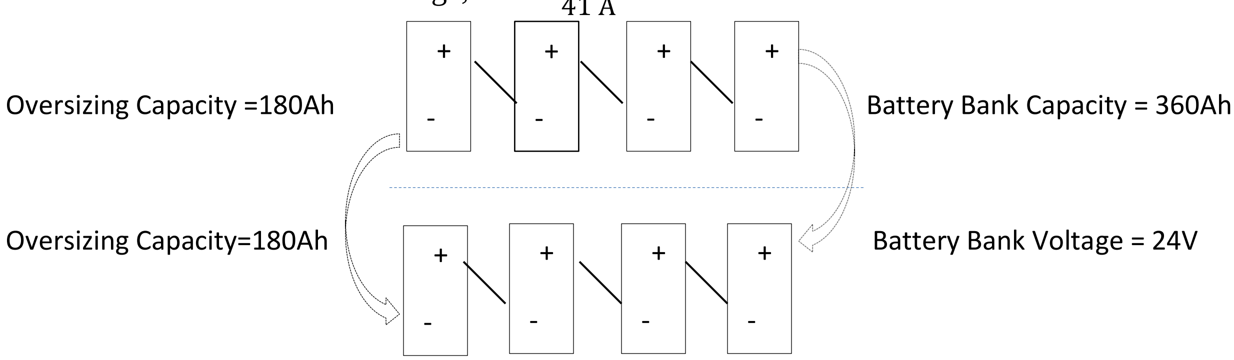
Using the above equations and load profile, the following results were obtained for lithium ion battery:

	Battery Bank Voltage		
Parameters	**V= 12 V**	**V= 24 V**	**V=48V**
Battery storage capacity (Ah)	3937.5	1968.75	984.375
Number of batteries	Rated 150 Ah $N_b = 26$	Rated 180 Ah $N_b = 11$	Rated 100 Ah $N_b = 10$
Discharge current (A)	82.03	41.0	20.50

Thus, the maximum hours of storage are:

1. *4 hours* if four 6 VDC lithium ion batteries are connected in series.
   If we take 6VDC Lithium ion batteries in series combination, then Maximum Hours of Storage is:
   Maximum Hours of Storage, $h = \frac{180 \text{ Ah}}{41 \text{ A}} = 4.39$ hours = 4 hours

2. *9 hours* if 8 lithium ion batteries are connected in the parallel and series combination. When the series-parallel combination of batteries is done, then ampere hour capacity of battery bank increases to 360 Ah (as shown below), and the maximum hours of storage are:
   Maximum Hours of Storage, $h = \frac{360 \text{ Ah}}{41 \text{ A}} = 8.78$ hours = 9 hours



Simulink/MATLAB simulation of a Photovoltaic System with a BESS

Figure 3 [18] shows a screen shot of the MATLAB based Simulink model comprising of photovoltaic (PV) cells and battery that serves as the base for assessing the characteristics of Battery Energy Storage System (BESS).

For the stand alone PV system, the PV Block shown is ideally considered when the modules are connected in parallel. Input parameters for PV module are taken from the Unisolar US-64 Solar Panel manufacturer with the following parameters [19].

- Maximum Power (P_{max}) = 64W
- Nominal Voltage : 12V
- Open Circuit Voltage, V_{oc} = 23.8Volts
- Voltage at maximum Power Point (V_{mpp}) = 16.5V
- Current at maximum Power Point (I_{mpp}) = 3.88 amp

The simulink model has the following information:

1. Irradiation Data – is assumed to be from "Ghost town" in the United States on any bright sunny day. This data is introduced in the form of an array in MATLAB and then put in the Simulink model by importing the data from MATLAB using "From Workspace" source block.
2. Generic Battery model is used for Lithium Ion (manufacturer: Saft VL34P) with the parameters extracted from the discharge characteristics curve.
3. Scope output for the complete Standalone Photovoltaic System is shown in Figure 4.

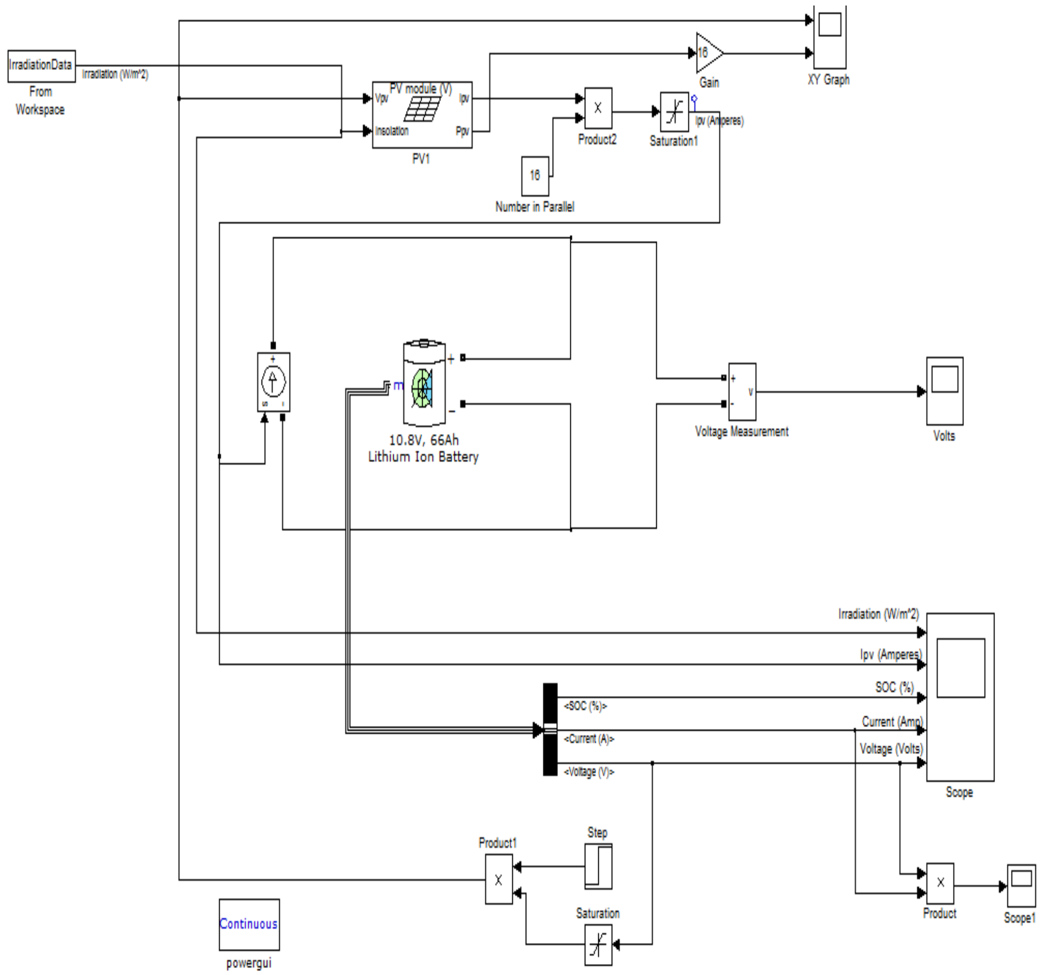


Figure 3. Simulink/MATLAB of a PV system with battery storage

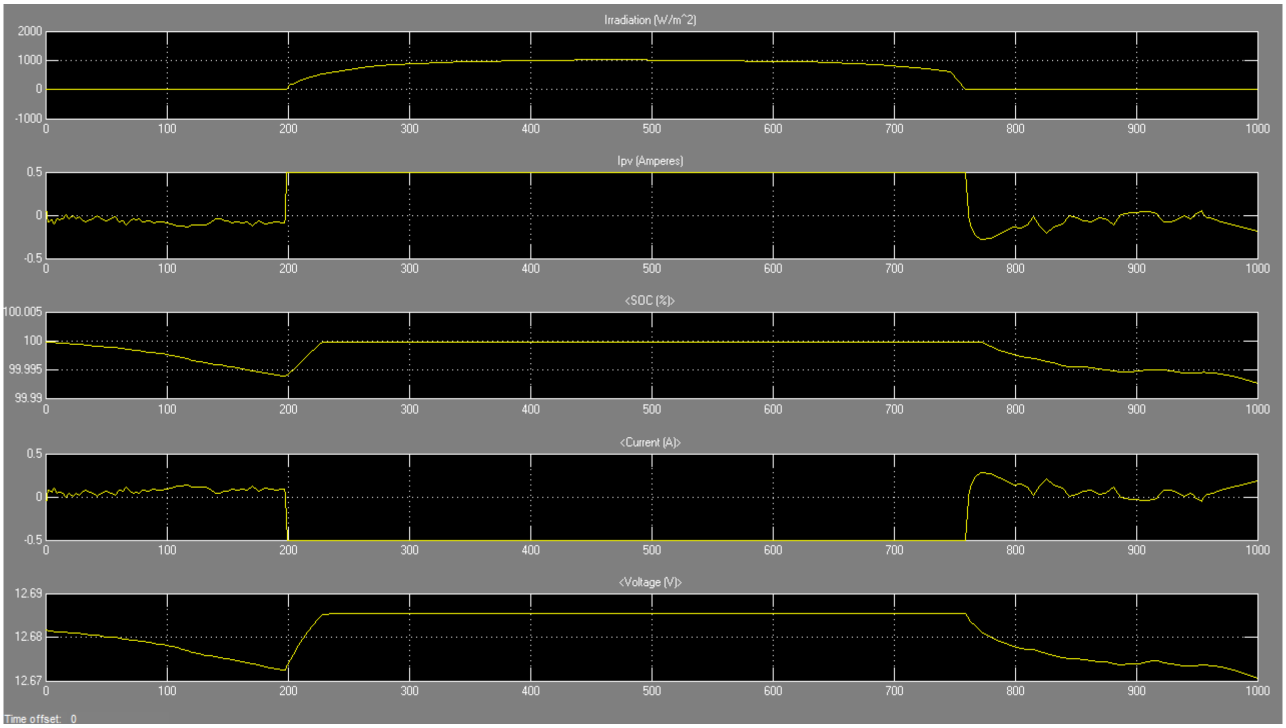


Figure 4. Output of simulation of a PV system with battery storage.

Output:

The first curve is "irradiation vs. time" which shows a maximum of 1000 W/m^2. The second curve shows "I_{pv} vs. time" and as expected a maximum I_{pv} is generated for a maximum irradiation. The third curve shows the state of charge (SOC) vs. time, where we can see the trend of irradiation. For example, when we ramp up to maximum irradiation the battery starts ramping up the charge and leveling off when irradiation levels off at about 1000 W/m^2. The fourth curve indicates the battery system current vs. time. The fifth curve shows the voltage of the battery vs. time.

Conclusions

This paper focuses on the essential aspects of battery technologies applied to residential applications. It shows an example of a typical household where the load was assumed in order to demonstrate the procedure to follow in order to determine the amount of batteries for a BESS. It is expected that when the battery voltage is larger, the amount of batteries for a constant load is lower. It was demonstrated that this was the case, as well as the discharge current that went from 82 A at 12 VDC to 20 A at 48 VDC. Also with the Simulink/MATLAB simulation shown in this paper we proved that the charge of the BESS follows the "irradiation." Consequently, we can conclude that solar systems will perform efficiently in areas where irradiation is strong. With the aggregate of residential BESS, utilities could use the energy stored for load peak shaving, frequency control, and stability.

This paper will be utilized as a base reference for a teaching module in our electric power systems program. We have arrived to the era of simulation, and we are not the exception. We chose to use Simulink/MATLAB because this program has a battery model integrated in its library and because our students are very familiar with the program and it is widely available to the students in the full version on our campus or as student version at a very low cost.

For future studies, one major player that was not mentioned in this paper is the Electric Vehicle (EV) and its effect on the residential load.

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