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DUCK CURVE AND BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEM

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Abstract

Due to huge price reduction and being the clean source of energy, solar energy is being deployed largely. While shifting towards the solar energy, not only the fossil fuel deployment has decreased, but also it has reduced the impact of gases released by using conventional sources of energy. However, the weather conditions affect the output power of PV generators. Moreover, PV generators can only generate electricity during the day. That is why it creates an imbalance in demand of load between day and night. Since the output of PV is time dependent, also there are various electric generators in the power plant fleet. This affects the actual benefits that could be had from solar PV in various regions. All this is shown by the Duck Curve. The Duck Curve was first published in 2013 by the independent operator of the California system (CAISO). The chart shows the impact of increasing the solar deployment. This chart also shows the ramp

Keywords:

Solar energy,

Duck Curve;

HESS;

Battery;

Supercapacitor.

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rates and range of the demand curve, which the conventional sources of energy would not be able to handle economically. In addition to this, due to higher solar deployment, more energy than the actual demand is produced which leads to over-generation. This would lead to its curtailment, which would increase its cost and reducing its environmental benefits. These issues can be overcome by adopting various energy storage techniques in the system depending upon the requirement of that system. The energy storage provides an efficient way to minimize the fluctuations in the generated power and delivering steady power to the grid. The utilization of the Hybrid Energy Storage System (H.E.S.S), which consists of a battery and a supercapacitor, is one of the methods used to store electrical energy for a short period. The batteries have a high energy density and a low power density. The high energy density of batteries means that they provide a constant current over a long period. However, the low power density of batteries limits their ability to provide immediate changes in energy requirements. Thus, as high intensity energy sources, super capacitors operate in modern H.E.S.S systems to compensate for the shortcoming of the batteries. Moreover, batteries are very expensive and fluctuations in their current result in reduction of their life cycle. Super capacitors can cover load current fluctuations, resulting in a smooth current of batteries.

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1. Introduction

1.1 Solar Energy and Duck Curve

Sustainable energy supplies are currently growing world-wide. Common sources of renewable energy are biomass, wind turbines, solar energy (PV), hydropower, concentrated solar energy (CSP), etc. There are various reasons for the popularity of renewable sources. These renewable sources are extremely suitable for saving fossil fuels. The demand for electricity worldwide has also increased due to urbanization, industrialization, population growth, and so on. Moreover, liberalization and deregulation of the energy market leads to more competition between energy producers. Solar energy, despite being a clean energy source, also has disadvantages. The production of solar energy depends on changing weather conditions. In addition, photovoltaic generators can only generate power during the day. That is why it creates an imbalance in demand of load between day and night. That is why energy management is an essential problem for a generation-based smart grid. Moreover, the installation of a plant based on solar energy requires a large area. However, the installation area has now reduced. In addition, some toxic chemicals e.g., Cadmium and Arsenic are utilized while manufacturing the photovoltaic panels. These chemicals have little effect on the environment, but disposal and recycling are under control in these chemicals.

Photovoltaic solar energy has revolutionized the energy production system. Its use not only stored fossil fuels, but also produced clean energy due to reduced emissions of certain pollutants and reduced greenhouse gas emissions. The production of photovoltaic solar technology, however, depends on time and the wide range of generators in the power plant fleet. There is much uncertainty about the real benefits of photovoltaic electricity in different regions.

In 2013, the California Independent System Operator (CAISO) analyzed the data and deduced the results in the form of a graphical representation termed as “Duck- Chart” depicting the overgeneration during the midday. The duck graph depicts the potential of photo voltaic to deliver energy greater than that can be utilized by the system.

Duck curve can be defined as a graphical representation of energy production during an entire day, indicating the variation in times for peak demand of energy and production of renewable energy. According to available data analysis, high demand was observed during the evening hours, with increased power consumption, resulting in a diagram resembling a silhouette of ducks. However, at that point of time, the solar is no longer available. As such, an alternate source to fulfill the energy need at that point of time has to be devised.

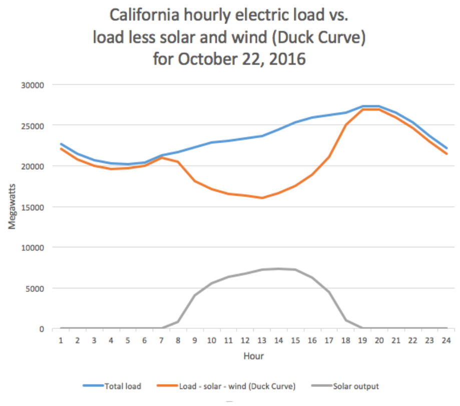

Figure 1: California hourly electric load vs. load less solar and wind (Duck Curve).

The curve shows the demand for electricity at any given time of day.The power companies supply the least amount of power overnight, then it ramps up in the morning (due to increase in demand), then at sunset, energy demand peaks.

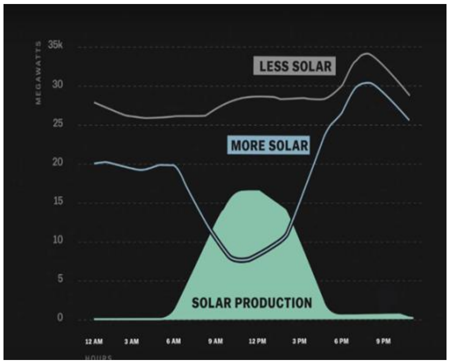

Figure 2: Decrease in demand due to increase in solar production.

The graph shows the solar production and the variation of demand curve over the day. The change in demand curve is shown with the increase in solar deployment over years. Maximum solar panel deployment is taking place and it is found that the sun produces most of the energy at the mid-day. Every year meets new solar capacity which makes mid- day demand dip lower and lower. This drop in the mid-day demand explains the formation of the "Belly of the Duck Curve".The graph shows the solar production and the variation of demand curve over the day. During the course of the day for which the sun is shining, solar floods the market and as the sun sets, solar energy production ends, just as the demand for energy typically peaks in the evening. Power plants then rapidly have to ramp-up the production to compensate for this increase in demand. This ramping up of demand from the mid- day belly (minimum demand) explains the formation of the "Neck of the Duck Curve".

Due to huge solar generation at the midday, the demand on the conventional grid decreases. Thus with increasing solar deployment, the Duck's belly gets fat and it starts hanging and getting closer and closer to the bottom of the chart. So the net load gets negligible around the midday. So the peak and intermediate plants shut down during that time. In addition to this, some base plants get ramped down too, and after some hours get back ramped up. Moreover, there is the requirement of reserve plants that act as buffer for emergencies. If so much solar deployment takes place that it starts eating up the reserve plants, then solar energy will be curtailed, and the grid will not accept it. Also there are economic reasons for the curtailment.

1.2Duck Curve and Over Generation

The CAISO duck scheme illustrates the challenge of absorption of solar energy, overproduction and reduced solar energy. In the graph, each net load line represents the difference of normal load and wind and photovoltaic generation. The belly of the duck represents the lowest net load period, with maximum photovoltaic power generation. The belly of the duck grows with the increase in photovoltaic compositions from 2012 to 2020. Although this chart does not directly represent the quantity of solar energy in 2020, the same can be estimated by the comparison of 2012 curve with the 2020 curve. In this case, the normal load (without PV and without any adjustment for load growth) appears to be around 22,000 MW, on March 31, 2020 at approximately 1-2 p.m., while the photovoltaic produces around 10,000 MW, thus leaving around 12,000 MW to be fulfilled by other sources. So in this case, photovoltaic can supply only 45% of the total demand during this period. The duck curve also refers to the period of excessive risk, which can lead to energy losses in the form of curtailment.

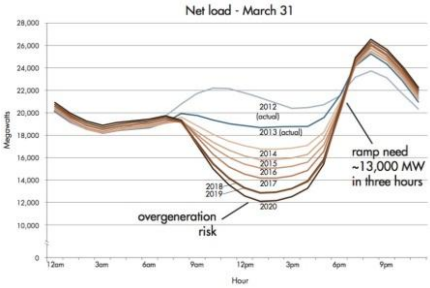

Figure 3: The official “duck chart” first published by CAISO in 2013.

A CAISO’s Duck Chart document does not specify the expected reduction size during this exact period. However, it justified the happening with following two reasons:

i) CAISO prepares for the upcoming ramps that take place at dusk and in the early morning using traditional sources of generation.

ii)

ii)Excessive generation and reduction occurs when the production of a non-distributable supply increases in times of low demand for electricity, usually at night. The second challenge is the need to include the production of all means of production such as wind and water power, and power plants that produce heat and electricity. Excessive generation can be the result of operational power plants to support local voltage problems and their reliability, as well as a number of institutional restrictions, such as long-term contracts and self-regulation of some power plants.

In total, these problems create an operational challenge that can be explained as the minimum generation problem that represents the economic and technical limits of hydroelectric and thermal power plants to reduce production, especially during relatively short periods of time, such as during peak hours of solar energy. In view of the economic challenges due to curtailment, it is important to test the extent up to which the curtailment can occur and how the curtailment can be reduced. Research into the relationship between system flexibility and reduction can help determine the potential contribution of solar energy to the energy needs of an area such as California.

Load curve is changed by the high intensity of photo voltaic during the day time which attains the shape of duck, and hence is called as Duck Curve. A large gap is observed between day-time load demands and night-time load demands. In the duck curve, more thermal generating units are required to work to meet demand during the night-time peak. In addition, TGs must start and work regularly due to the unbalanced load status. Thus, using the TGs optimally is of very much significance. Load balancing is a requirement for optimum use of TG units. In addition, the ESS and demand-driven loads can yield useful results. The compliance unit (UC) optimization was used by TGs using storage systems by load balancing researchers. The proposed [16] compensated the load using flywheel storage. However, it did not consider UC. In order to reduce the costs and emissions,[17] suggested thermal unit commitment by taking wind and hydropower into account. However, it did not consider demand side and CSP. Reference [18] worked on UC model is driven by demand, but does not run on CSP and PSH and PVs and carbon dioxide emissions. Reference [19] was worked upon in unit commitment and energy storage models. However, it did not consider CSP, demand response, duck curve, etc. Reference [20] worked on BES and demand side response with thermal UC in order to optimize the BES. However, they did not considered CSP, PSH, Duck curve and CO_2 emissions. Also their methodology was not able to increase the renewable power to the smart grid. Reference [21] worked on UC model due to higher deployment of renewable energy resources. However, they did not considered energy storage systems and demand response. Reference [22] examined thermal unit commitment, energy storage systems, and renewable power. However, the model could not increase the renewable power generation. Reference [23] considered the UC of nexus of energy water. However, they did not consider the costs of fossil fuels and that of start-up.

1.3Hybrid Energy Storage System (H.E.S.S)

The hybrid power system opens up a series of energy and energy management options in comparison to a stand-alone photo voltaic system. When there is less solar radiation or more fluctuations in the photovoltaic output, the fuel cells cover the primary load to guarantee uninterrupted power supply. But due to the slow dynamics of the fuel cell, hybridization with the battery that responds faster can help the system to fulfill the required energy demand. Thus, use of the battery with the fuel cells improves the performance and service life of fuel cells because the load changes are absorbed by the battery more quickly and thereby preventing the starvation of the fuel cell.

To achieve a faster response, the supercapacitor can be integrated into the system. Supercapacitors have fast charging and discharging capability, highly reversible control functions, high energy density and low relative power density in comparison to the batteries. Due to the unique performance characteristics, the supercapacitor can reduce the battery from frequent and repeated charging and discharging, thus guaranteeing a longer life span of battery. The extended peak loads are taken by the battery, while the shorter bridge power functions are processed by the supercapacitor. It can also provide superior power quality to compensate for the high voltage sags, which act as a buffer for the peak or peak current.

Because the principle of working of batteries and supercapacitors is different, the supercapacitor is able to run without power loss for a long time. The batteries are notorious for the loss of power with prolonged use. Therefore, the basic operating characteristics of the system components depend on two characteristics: energy density and power density. The gravimetric energy density of the system is defined as the amount of energy (WH) that could be stored in the system per unit mass (kg). The gravimetric power density of a system is defined as the amount of energy (W) that the system could provide per unit mass (kg). Given the little transient behavior on the constant and stable load, one of the most essential features of the system is its energy density. The system must be able to fulfill the load conditions as long as possible. However, when there is transient behavior of the load profile, it becomes necessary to meet the immediate energy demand and power density becomes an important feature of the system..

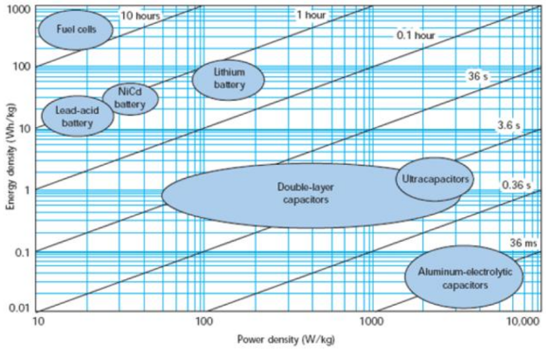

Figure 4: Ragone diagram with different energy storage technologies. Vertical axis is the specific gravimetric energy density, horizontal axis is the specific gravimetric power density. The inclined lines specify the discharge time into a specific load.

The Ragone diagram in Figure 4 briefly describes the various energy storage properties of different technologies. Fuel cells occupy the upper left position with an energy density of a maximum of 1 kW / kg and an operating time of more than 10 hours, but with a relatively low energy density of 10-20 W / kg. The conventional batteries have a power density of about 10 W / kg, an hour of operation of one hour, a power density of 10-200 W / kg and low pressure low pressure. Lithium ion batteries also have the highest energy density. Supercapacitors work to bridge the distance between batteries and traditional electrolytic capacitors. They have a relatively low power density and a much shorter service life than batteries and fuel cells, but they can have a density of up to 5 kW / kg.

Supercapacitors can therefore be integrated into a range of different applications, not only to increase the power density of the power supply system, but also to protect the batteries and fuel cells from large current peaks. Some applications include memory maintenance systems, communication applications, and uninterrupted power supply by hybrid vehicles, traction systems used in trains, subway systems, larger power generation systems, etc.

1.4 Battery/Supercapacitor H.E.S.S

For the fluctuating solar irradiation and variable load conditions on a PV stand-alone grid, it is necessary to use the energy storage system (ESS). Lithium-ion battery (Li-ion) and lead-acid battery (LA) are the most widely used energy storage technologies employed in residential power systems. Li-ion batteries have a higher energy density and better efficiency and a longer lifespan than LA batteries, but they are relatively expensive and immature when employed for large scale packing. For comparison: the LA battery bank is more suitable for an independent energy system, especially in the case of national electrification due to the low costs and the better thermal stability. By employing a single energy storage technology, limitations in terms of cost, power, energy density and lifetime will be faced. So use of Hybrid energy storage technologies is being proposed in order to overcome these limitations.

The hybridization of various energy storage technologies has proven to be one of the most promising ways to reduce the stress due to charging and discharging the battery by directing short-term fluctuation in power to another form of energy storage system such as supercapacitor. The supercapacitor contains a high energy density, a short discharge time and an almost unlimited service life.

One of the solutions is to use an hybrid energy storage system with battery and supercapacitor. The super capacitor has a higher power density than the battery, so the supercapacitor can supply more current over a shorter period. On the other hand, the battery is characterized by a higher energy density then the supercapacitor, so that it can deliver less energy for a longer period of time. Batteries are used to meet power requirements for a relatively long time, with high energy storage but with limited power. Superior capacitors are used to meet the direct energy demand, given their ability to deliver high levels of energy while the energy storage rate is much lower. In addition, the super condenser can act as a buffer against rapid fluctuations and high power.

The intended working of a battery- supercapacitor hybrid energy storage system is as follows:

The battery must provide approximately a constant load current, which prevents dips in the terminal voltage and reduces the internal ohmic losses, while the supercapacitor must match the battery with the load by supplying the dynamic current at an average of zero. During a high load requirement, both the battery and the supercapacitor charge the load, while during a low load the battery charges both the load and the supercapacitor. This should reduce the current and voltage ripple of the battery.

1.5Battery- Supercapacitor H.E.S.S Topologies

The combination of the battery and supercapacitor in H.E.S.S can offer a suitable fit that can cover a wide range of power and energy requirements in photovoltaic systems. Different types of topology are possible for a range of batteries and supercapacitor to DC bus. The circuit topologies for the H.E.S.S can be classified as shown in the table below:

Table 1: Classification of HESS topologies.

HESS topology		
1.Passive Parallel Topology	2.Fully Active Topology	3.Semi Active Topology
	• Series Topology I • Series Topology II • Parallel Topology • Multi input Converter Topology	• Supercapacitor/ Battery Topology • Battery/ Supercapacitor Topology • Hybrid Diode Topology

In passive parallel topology, the ESS comprising of battery and supercapacitor are connected in parallel and directly coupled to the DC bus. No DC-DC converter is used in this case.

In fully active topology, the ESS comprising of battery and supercapacitor are interfaced by active component such as bi-directional DC/ DC power converter which actively controls their power flow. This makes the control of the system more accurate.

In Semi- Active topology, DC bus and any one of the energy storage element among the HESS are decoupled through a bi-directional DC/ DC power converter. Thus only one bi-directional DC/ DC power converter will be used in this topology.

Among the different topologies of the battery supercapacitor HESS topology, use of many bi-directional DC/ DC power converter would increase the energy losses, thus decreasing the efficiency (except when DC/ DC power converter is connected in series with supercapacitor). In addition, if bi-directional DC/ DC power converter is not used meaning that passive topology is used, it would be difficult to make full use of best performance of the on- board energy components. So, Semi-Active topology employing only one bi-directional DC/ DC power converter is the ideal topology to be considered for the system.

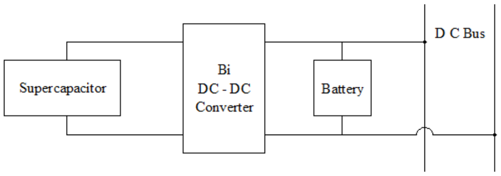

Figure 5: Supercapacitor/ Battery Semi Active HESS topology

2. Gap Analysis of Stand Alone PV Grid

Increasing the use of solar energy and decreasing the use of conventional sources is a great news for green power, but there are a few problems which are listed below:

i. Grid instability in the duck’s neck:

At the dusk, the traditional power plants must take the load. As the solar disappears for the night, peak plants must go from zero to full power. Greater penetration of solar energy demands greater load shifting. Again, the equation must be balanced or the users will be in the dark. It is hard to spin up increased number of peaking machines over a large geographical area without introducing instability.

ii. Grid instability in the duck’s belly:

The national power-grid comprises of thousands of generators. As solar takes the load (belly of duck) many of these generators will be secured. For example, the peak plants are designed specifically to manage the peak load of the day. However, if the trend continues, a very bad situation could occur in the year 2035 or 2040. Here, all traditional generators would be secured and the power flow would go negative. This is not a good way to balance the equation. This problem has already happened in Hawaii causing instability problems.

iii. Poor efficiency on the fossil fuel side:

The larger baseline power plants are optimized to run at a specific power. Deviation from this power level results in reduced efficiency. For example, in the year 2030 the green baseline generator power would be cut in half. The energy not covered by solar would be covered by less efficiency peak plants. It is to be noted that it can take many hours even days for a baseline generator to change its output power. This reduction in baseline power demand is death to nuclear and coal. At reduced power levels they are not economically viable.

iv. Financial:

Investors expect a return on their money. The peak plants will sit idle for a large portion of the day. Idle machinery does not make money. Yet, these plants cannot be eliminated as they are needed at night. Someone will need to pay.

3. Problem Statement

Overcoming over-generation as indicated in Duck Curve by some means of energy storage for enabling greater penetration of solar energy.

4. Research Method

The research methodology is based on choosing topology of the Hybrid Energy Storage System (H.E.S.S) based on battery and Supercapacitor. After that the required simulation is performed in the MATLAB/ Simulink which is discussed below.

The control strategy is implemented for the Semi Active topology which is depicted in Figure 5. The formulated topology in MATLAB/ Simulink is shown below:

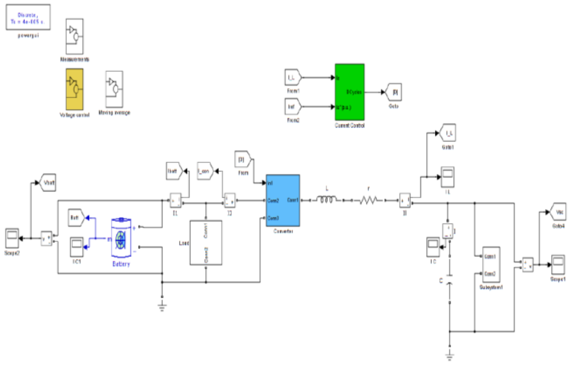

Figure 6: Battery- supercapacitor Semi-active H.E.S.S model formulated in Simulink with dynamic average representation of the converter.

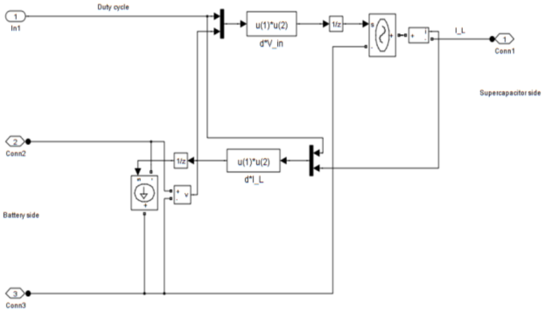

Figure 7: Dynamic average model formulated in Simulink.

The control strategy that is discussed and applied is based on power smoothing with moving average technique and over/undervoltage protection. This control strategy is simulated in MATLAB/ Simulink. However the simulation was not applied practically, it was limited to the software only. The specification of the supercapacitor model that was used in this simulation is BMOD00165, the former model from Maxwell Tech., and the design of converter is also based on this model.

4.1. Control Strategy

The control strategy is based upon power smoothening and over/undervoltage protection. These are discussed as follows:

4.1.1 Power Smoothing with moving average technique

The fast transients that appear in the voltage and current of the battery can be efficiently removed using this technique. If P_{load} represents the instantaneous power i.e. demanded by the load and averaged power is represented by P_m then:

$$P_m = \frac{1}{Tm} \int_{t}^{t-Tm} Pload \, dt$$

Here, T_m is defined on the basis of the applied loading and is known as the timing window. P_m represents the power profile of the battery. The procedure for generating the current reference is explained as follows:

i. Firstly, the difference of the calculated value of the moving average power, P_m and the actual load power, P_{load} is obtained. This difference represents the amount of power that should be covered by the supercapacitor.

$$P_{SC,ref} = P_{load} - P_m$$

ii. Secondly, in order to calculate the current reference that will go to the controller, I_{ref}, the amount of power that should be covered by the supercapacitor, $P_{SC,ref}$ is divided by the measured instantaneous supercapacitor voltage $V_{sc.}$

$$I_{ref} = \frac{PSC,ref}{VSC}$$

I_{ref} is then sent to the controller where the measured inductor current I_L is subtracted, producing an error signal which is sent to the PI-controller. The formulated current reference generator in Matlab/Simulink can be seen in Figure 8.

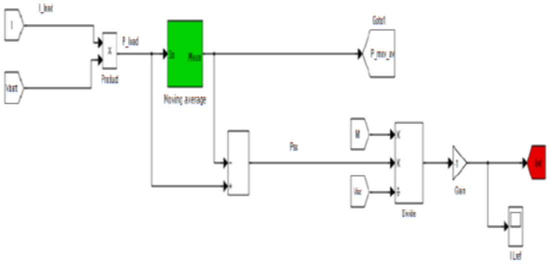

Figure 8: Current reference generator with moving average in Simulink.

4.1.2 Over/Undervoltage protection

The DC voltage of the battery can exceed the nominal voltage of 48 volts. If the supercapacitor's state-of –charge is almost 100%, this can result in a super-high voltage voltage that is higher than the nominal voltage. This can ultimately lead to supercapacitor damage.

Therefore, a supercapacitor protection is required for the voltages exceeding the nominal voltage. It is also necessary with under voltage protection at about half the nominal voltage, since a constant discharge below this limit can cause the supercapacitor damage.

The control strategy for the voltage protection in the Simulink model is formulated as follows. One way is to make use of different logical blocks that take the state-of-charge of the supercapacitor denoted by SoCsc and the load current denoted by I_{load} as inputs. After that these produce a dimensionless value K, whose value lies between 0 and 1 depending upon some rules that are also discussed. Once the value of K is obtained, then this value could be multiplied with the current reference denoted by I_{ref} that leads to the different operating modes of the supercapacitor depending upon the state - of - charge and the type of loading of the supercapacitor.

The modified current reference is then:

$$I'_{ref} = K.I_{ref}$$

The set of rules could be formulated as follows:

$$K = \begin{cases} 0 & \text{if Iload} < 0 \text{ } and \text{ } SoCsc \geq 100\% \\ -20\text{SoCsc} + 20 & \text{if Iload} < 0 \text{ } and \text{ } SoCsc > 95\% \\ 1 & \text{if } 95\% < SoCsc < 30\% \\ 20\text{SoCsc} - 5 & \text{if Iload} > 0 \text{ } and \text{ } SoCsc < 30\% \\ 0 & \text{if Iload} > 0 \text{ } and \text{ } SoCsc \leq 25\% \end{cases}$$

The five operating regions define the set of rules. These are discussed as follows:

i. The first rule defines the fixed maximum upper limit at SoCsc = 100%, where K= 0. The current reference now becomes zero, which prevents overcharging of supercapacitor.
ii. The second rule defines the upper transition zone, where K smoothly breaks down to zero as SoCsc goes from 95% to 100%. The value of slope and constant, here equal to 20, indicates the speed at which M changes in this area.
iii. The third rule defines the normal operating zone where K = 1, as SoCsc goes from 30% to 95% and therefore making $I'_{ref} = I_{ref}$.

iv. The fourth rule defines the lower transition zone, where K smoothly breaks down to zero as SoCsc goes to 30%. The value of slope is 20 that of constant is -5, indicates the speed at which K changes in this area.

v. The fifth rule is defined when SoCsc < 25% and produces K = 0. The current reference now becomes zero, which prevents overcharging of supercapacitor.

However, K = 0 is not minimally required when the net energy transferred to the system i.e., load is negative. Regardless of SoCsc, the energy that is supplied from the load should be used to charge the supercapacitor. Therefore, when $I_{load} < 0$ and SoCsc < 25%, the logical block follows rule 3 thereby, producing K = 1.

Similarly, when net energy transferred out of the system i.e., load is positive, the supercapacitor should discharge in a way to assist the battery. Therefore, when $I_{load} > 0$ and SoCsc = 100%, the logic block follows rule 3 thereby, producing K = 1.

These rules forming the voltage protection control in the form of blocks is shown with the help of simulation. The Simulink diagram for the same is shown in the figure 9.

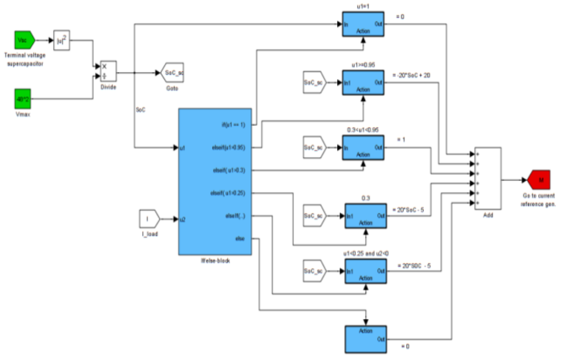

Figure 9: Voltage protection control block formalized in Simulink.

3. Simulation Results

To see the results of the control strategy, a semi-active topology of the Battery-Supercapacitor H.E.S.S topology is simulated with random changes in the load during a 10 minute time window. First the moving average window is set at Tm = 60s. The simulation result is shown in Figure 10.

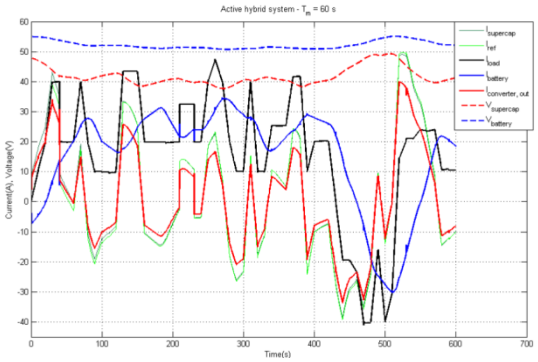

Figure 10: Simulation of Semi Active Battery- Supercapacitor H.E.S.S topology with fluctuating load. System current and voltage as a function of time. Tm = 60s.

When $I_{load} > 0$, there is a net power demand and energy is transferred from the system to the load. When, $I_{load} < 0$, net power is supplied from the load to the system. The current coming from the converter output on the battery side, $I_{converter;out}$, is added to the battery current, $I_{battery}$, represented by the solid blue line. When adjusting the moving average time to Tm = 120s, gives the result shown in figure 11.

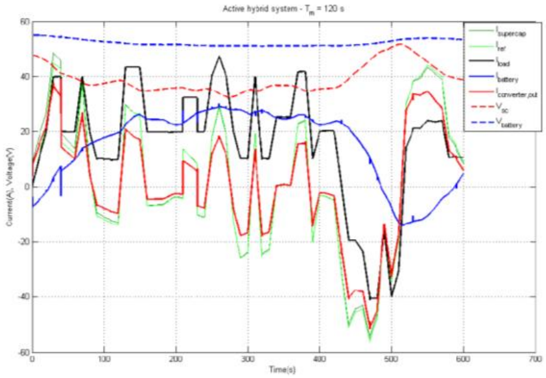

Figure 11: Simulation of Semi Active Battery- Supercapacitor H.E.S.S topology with fluctuating load. System currents and voltages as a function of time. Tm = 120s.

One way to compare the level of utilization of supercapacitor in Semi Active Battery-Supercapacitor H.E.S.S, is to calculate the absolute value of the charge in terms of amp hours from and to supercapacitor respectively in the semi-active and semi-passive system. To check the utilization level of the battery, the accumulated amp hours immediately calculate the battery discharge level in a specified time window, without taking the absolute value.

To calculate amp hours, currents of battery and supercapacitor, Ibattery, and Isc are integrated over time. The accumulated amp hours can be seen as a function of time in Figure 12. The absolute value is used because the amp hours collected by the supercapacitor will be almost equal to zero if SoCsc hardly changes in the specified time window.

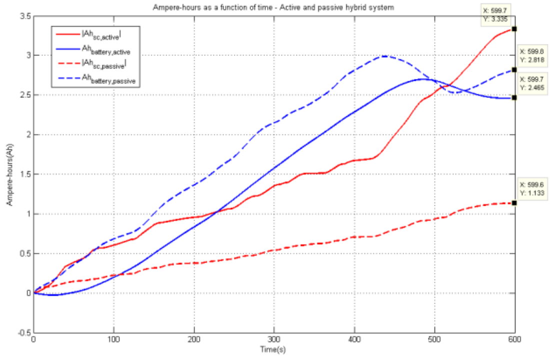

Figure 12: Accumulated ampere-hours as a function of time, for the Semi Active Battery-Supercapacitor and Passive H.E.S.S topology respectively. Calculated from simulation over 10 minutes modified simulation time with fluctuating load. Active system with Tm = 120s.

By exposing the Semi Active Battery- Supercapacitor H.E.S.S topology to the same pulse train load as that of the passive hybrid system, we get the result shown in Figure. 13. The duty cycle, D=0.1 and the pulse period, T = 7.3 seconds. A moving average, Tm= 7.3 seconds has same value as that of the pulse period.

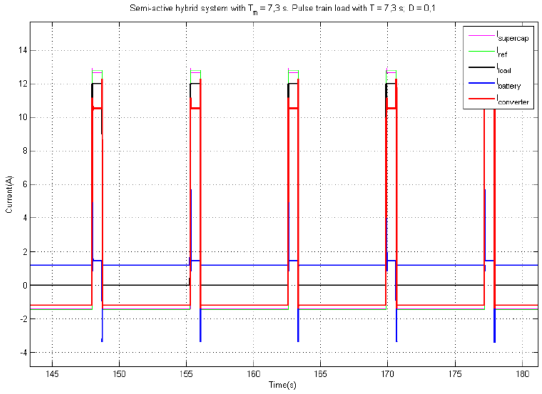

Figure 13: Exposing the Semi Active Battery- Supercapacitor H.E.S.S topology Semi –Active H.E.S.S topology to a pulse train load with T = 7.3 s and D = 0.1. Steady state operation. The moving average is set to Tm = 7.3 s.

Given the same load, the result of a progressive average reduction to Tm = 2 seconds is shown in Figure 14.

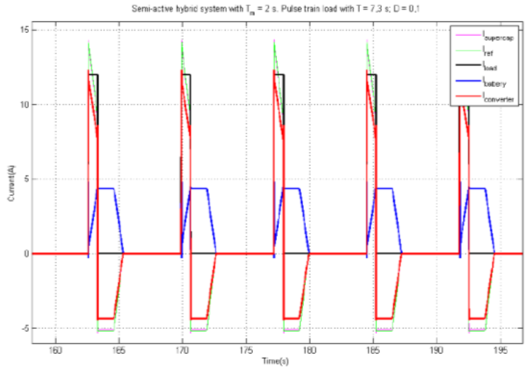

Figure 14: Exposing the Semi Active Battery- Supercapacitor H.E.S.S topology SAHS to a pulse train load with T = 7.3 s and D = 0.1. Steady state operation. The moving average is set to Tm = 2 s.

5. Simulation Discussion

The simulation result with Tm = 60 seconds is shown in Figure3.9. The battery current, $I_{battery}$, and output current, $I_{converter,out}$, are added during simulation to meet the desired load current. Current due to the supercapacitor side of the converter, I_{sc}, is decided by the reference current signal, I_{ref}. They adequately follow the same path in the time window, except for a slight skew in the first minute, because the system has not yet reached the stable operational state at that time.

When the $I_{converter}$ and I_{sc} is positive, the supercapacitor is discharging and the converter is in Buck mode. Note thatinitially the $I_{battery}$ is negative and $I_{converter;out} > I_{load}$ so, at this stage, the battery is charged by supercapacitor. The moving average is catching up with load after 60 seconds and $I_{battery}$ stabilizes around the moving average of the load. When $I_{battery} > I_{load}$, due to the 60 second delay in the moving average, the $I_{converter}$ and I_{sc} turn negative and the converter enters into Boost mode, so that the super capacitor is charged by the battery.

The terminal voltage of battery, $V_{battery}$, is maintained with a stable small ripple in the time window, while the terminal voltage of the supercapacitor, V_{sc} fluctuates more. If the load becomes negative after 430 seconds, the net power is transferred to the system and both the super capacitor and the battery are charged. Note that $V_{battery}$ and V_{sc} increase at this stage, so the charging status for both the battery and the super capacitor increases.

The maximum charge state for the super capacitor is approximately around 270 seconds when Vsc = 37.7V, ie SoCsc = 63%. Thus, the superconductor is never used below its maximum potential, i.e., up to 75% of the stored energy is discharged by discharge near SoCsc = 50%. This shows that the control strategy can be optimized to utilize more operating range of the supercapacitor. As expected, the increased utilization of the supercapacitor and a smoother battery current is obtained by using the same load profile and increasing the moving average to Tm = 120 seconds, as shown in Figure 3.10. When intervals between transients become shorter, the moving average time can be shortened.

Thus, the battery current, $I_{battery}$ is smoothed due to the presence of the supercapacitor. In addition to this, the battery is protected from the step changes in voltage and current. Figure 3.11shows the comparison of the Semi Active battery –Supercapacitor H.E.S.S topology with Tm = 120s and the Passive H.E.S.S topology are by plotting the transferred amp-hours to and from the supercapacitor and the discharged amp-hours from the battery. It is clearly observed from the figure that the supercapacitor is utilized to a greater extent in the Semi Active battery – Supercapacitor H.E.S.S topology, while in case of passive topology, the operating limit of supercapacitor is limited by the system voltage.

6. Conclusion

The utilization of renewable sources of energy like solar deployment has proved to be beneficial in many aspects like lowering customer and utility costs, creating jobs, and decreasing environmental impacts. Utilization of renewable sources of energy has more focus on reducing the green-house gases and to ensure affordable and reliable grid operation. Even though the photovoltaic solar energy market has seen an astronomical level of growth and cost reduction over the recent years, there are still many economic realities and technical challenges that need to be reconsidered so that resources are shared with the traditional generation. Due to the increase in solar energy generation, utility companies have to find ways to balance supply and demand on the grid. This is due to the dependence on solar energy for the presence of the sun. That is why energy production must be ramped up at sunset. Moreover, during noon when solar energy is abundantly available, the energy produced is more than the demand. This leads to over-generation. This is explained by duck chart. The duck chart shows that the partial dependence on the conventional sources and partially on solar energy is not economical. As such, we must fully switch to utilize solar energy by adopting some ways to fulfil the ramp up needs and storage of the over-generated energy. This ultimately, avoids the over-generation and curtailment, along with its environmental benefits. In this thesis Duck curve along with its utility challenges is explained. In addition to that the solution to over-generation caused by solar energy, by using hybrid energy storage technologies has also been discussed. The storage of energy provides an efficient way to minimize the fluctuation in electricity and delivery strategies of electricity to the respective distribution network. The utilization of the hybrid energy storage system (H.E.S.S), consisting of a battery and a supercapacitor, is one of the methods for storing electrical energy. It has been observed that the supercapacitor has unique properties that other energy storage technologies, such as batteries, can complement. Considering its high recyclability, high energy density, fast charging and discharging capacity, highly reversible functions and relatively low internal resistance, it is an effective alternative to hybrid feed systems.

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