Optimal energy management strategy: standalone photovoltaic system

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***Abstract*- This paper proposes a design for a renewable energy standalone hybrid power plant that is fed by a photovoltaic (PV) source with supercapacitor (SC) energy device and is suitable remote areas away from national grid. The PV is used as the main generator & the SC functions as an auxiliary source for supplying the (transient & steady-state) power deficiency of the PV. In hybrid system PV & SC both are connected to the DC bus through a dc/dc converters and optimize the combination of the PV & SC for a given solar radiation and load profile employing MATLAB/SIMULINK Software.**

Keywords* - *Photovoltaic, Supercapacitor, Converters

I. INTRODUCTION

A growing interest in renewable energy resources have been observed for several years. The alternative energy sources are non-polluting, free in their availability and continuous. These facts make the alternative energy sources attractive in rural or energy deficient areas where the cost of connection to the grid in remote locations cannot be justified. Today, the most developed source of alternative energy systems are: the solar energy and the wind energy. However, these renewable energy sources suffer from some deficiencies when used as standalone energy sources .The natural intermittent properties of wind speed and sunlight causes power fluctuations in wind turbine and photovoltaic panels. For these reasons, energy storage is required to manage the power flow and to maintain system instantaneous power balance. Generally, the energy storage systems in standalone renewable sources can be batteries or super capacitors. In comparison to standard batteries, energy density of super capacitors is lower by an average factor of 10. However, their energy density is compatible with a large range of power applications that need high instantaneous power during short periods of time. Another advantage in the use of supercapacitors rather than batteries is their life time and their number of cycles, which is at least 500 times more than that of standard batteries. In addition supercapacitors are electrical energy storage devices that offer significantly better energy densities than conventional capacitors. The charge and discharge times of super-capacitor varies from fractions of a second to several minutes while providing maintenance free operation. Supercapacitors provide the lowest cost per farad, extremely high cycling capability and are environmentally safe.

II. PROBLEM FORMULATION

Now days, people are highly depending on fossil fuel to generate electricity due to its cost effective and simple combustion process. Even though this source is able to generate huge amount of electricity in just a single location, yet the outcome of using this source is worrying as it could affect the environment by producing high emission of carbon dioxide which contribute to global warming, air pollution and acid rain. From here, it can be seen by using alternative energy which is sustainable and renewable is the most efficient way of generating electricity besides using fossil fuel. This renewable energy includes solar, wind, tidal, biomass, and etc. Next is the difficulty of supplying electricity to remote and inaccessible areas. There are certain areas where to implement grid extension high cost will in occur and technically not practicable.

Table1: Comparison between supercapacitor & battery

Property	**Supercapacitor**	**Li-Ion Battery**
Charge time	1 – 10 seconds	10 – 60 minutes
Cycle life	1 million/ 30,000 h	500 & higher
Cell voltage	2.30 – 2.75 V	3.6 – 3.7 V
Energy Wh/kg	5 Wh/kg (typical)	100 – 200 Wh/kg
Power kW/kg	Up to 10 kW/kg	1 – 3 kW/kg
Cost per Wh (typical)	€15 (typical)	€1.50 (typical)
Service life	10 – 15 years	5 – 10 years
Charge temp.	-40°C – 65°C	0°C – 45°C
Discharge temp.	-40°C – 65°C	-20°C –60°C

Standalone photovoltaic system itself is not reliable and inefficient. This is mainly because the output of the panel is highly depending on weather conditions. If there is no sun or cloudy days, the output of the panel will be affected. Similar problem also occur during at night where the irradiation and temperature is very low. In order to overcome this matter, storage element such as batteries, fuel cell or supercapacitor can be used to provide power during peak demand and low irradiation period.

III. STANDALONE HYBRID SYSTEM

The Simulation model of standalone hybrid system is shown in fig 5 which consists of photovoltaic cell, supercapacitor, dc/dc converters.

1) Photovoltaic cell -Photovoltaic cell is a non-linear source, behaving as a constant current source when output voltage is low and constant voltage source for a high output voltage. Based on mathematical expressions and its equivalent circuit as shown in fig 1, a Simulink model of PV cell is designed which is shown in fig 2.

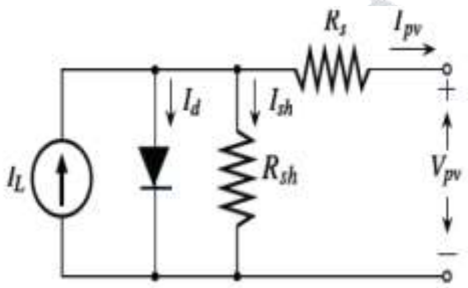

Figure1: Equivalent circuit of PV cell

Mathematical Expression :-

The mathematical model can be expressed as:

$$I = I_{ph} - I_{sat}\{\exp\left[\frac{q}{AKT}(V + IR_s)\right] - 1\} \quad (1)$$

Equation1 shows that the output characteristic of a solar cell is nonlinear and vitally affected by solar radiation, temperature and load condition.

Photocurrent I_{ph} is directly proportional to solar radiation G_a

$$I_{ph}(Ga) = I_{sc}\frac{G_a}{G_{as}} \quad (2)$$

The short circuit current of solar cell I_{SC} depends linearly on cell temperature

$$I_{sc}(T) = I_{scs}[1 + \Delta I_{sc}(T - T_s)] \quad (3)$$

Thus I_{ph} depends on solar irradiance and cell temperature

$$I_{ph}(Ga, T) = I_{scs}\frac{G_a}{G_{as}}[1 + \Delta I_{sc}(T - T_s)] \quad (4)$$

I_{sat} also depends on solar irradiation and cell temperature and can be mathematically expressed as follows

$$I_{sat}(G_a, T) = \frac{Iph\ (Ga,T)}{e\left(\frac{Voc(T)}{Vt(T)}\right) - 1} \quad (5)$$

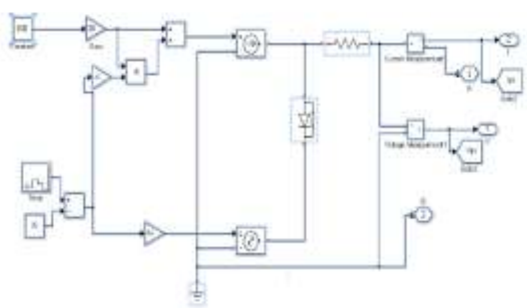

Figure 2: Simulation model of PV cell

Table 2: Specifications of PV cell

Internal Parameters	Specification
Series resistance(R_s)	8e-3Ω
Parallel resistance (R_p)	0Ω
Temperature	25°C
Irradiation	800w/m^2
Forward voltage (V_f) of diode	0.8V
Quality factor	1.5

2) Supercapacitor - Supercapacitors are based on the double-layer capacitance concept, first described by German physicist Hermann von Helmholtz, in 1853. Later, in 1966 researchers at Standard Oil Company, Cleveland, Ohio (SOHIO) developed a multi-farad device. However, the first high-power electro-chemical capacitors were developed for use in a variety of military applications by Pinnacle Research Institute (PRI) in the USA under the name "Ultracapacitors" between 1982 and 1989. The ultracapacitor employs the same principles as normal capacitors but its capacitance is in the thousands of farads range. The ultracapacitor is constructed of two electrodes immersed in an electrolyte with an ion permeable separator placed between the electrodes to prevent electrical contact, but to still allow ions from the electrolyte to pass through. Figure 3 shows the schematic diagram of Supercapacitor. In the ultracapacitor the charge is stored in the ionic layer that forms at the interface between each of the electrodes and the electrolyte, hence the accumulated charge forms an electric double layer. The large capacitance of the ultracapacitor is as a result of the high surface area of the electrodes. The most common electrode material used is highly porous activated carbon with a surface area of $2000m^2$/gram due to its low cost, high surface area and availability. The development of the carbon electrode material influences its porous structures.

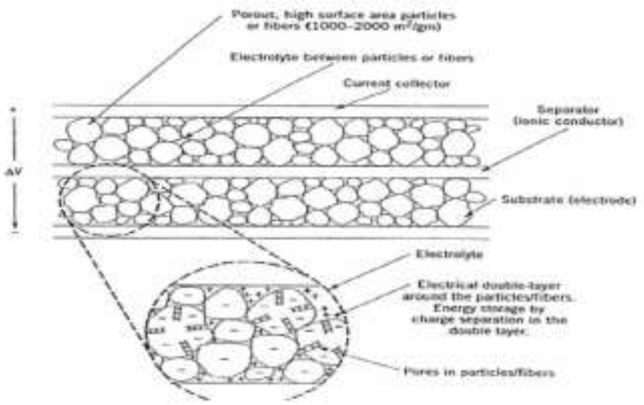

Figure 3: Schematic diagram of supercapacitor

It is the accessibility of the pores to the electrolyte that is important, if the pores are too small for access by the electrolyte ions they will not contribute to the electric double layer. Capacitance of a capacitor is proportional to the surface of its plates and dielectric constant of the substance contained between those plates, and inversely proportional to the plate separation.

$$C = \in_r \in_\circ \frac{A}{D} \qquad (6)$$

Where, C is the capacitance, $\in_r$ is the dielectric constant of free space, $\in_\circ$ is the dielectric constant of the medium between the two layers, A is the surface area, and D is the distance between the two layers and the simulation model is shown in figure4.

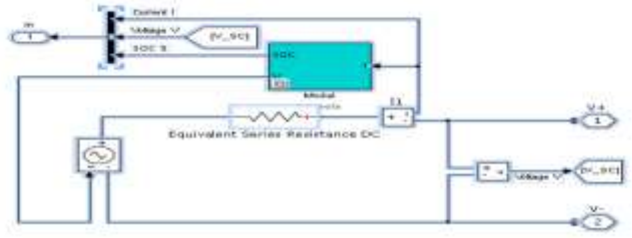

Figure 4: Simulation model of supercapacitor

MODEL ASSUMPTION

1) Internal R&C are assumed to be constant during charge and discharge cycles.
2) No temperature effect
3) No aging effect
4) Charge redistribution is same for all values of voltage
5) Current through supercapacitor is assumed to be continuous

Table 4: Advantages & Disadvantages of Supercapacitor

Advantages	Disadvantages
Virtually unlimited cycle life (can be cycled millions of time)	Low specific energy (holds an energy fraction of a regular battery)
High specific power (low resistance enables high load currents)	Linear discharge voltage (prevents using full energy spectrum)
Charges in sec(no end-of-charge termination required)	High self-discharge (higher than most batteries)
Simple charging (not subject to overcharge)	Low cell voltage (requires serial connection with voltage balancing)
Excellent temperature charge & discharge performance	High cost per watt

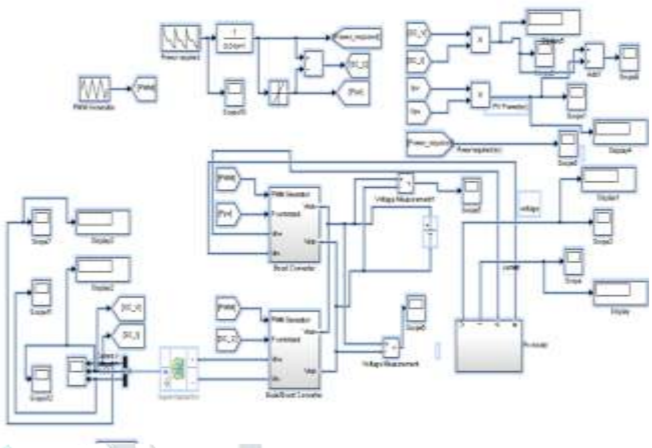

Figure 5: Simulation model of PV-SC system

IV. RESULTS & DISCUSSIONS

As the standalone hybrid PV-SC system is designed by using MATLAB/Simulink software. The main aim is to manage power efficiently between the power generated by PV-SC system and power demanded by load, irrespective of change in irradiation.

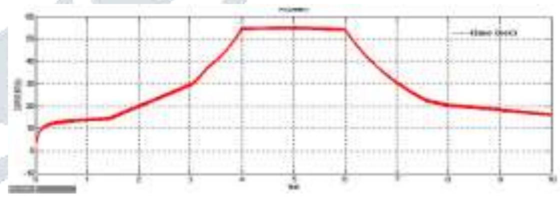

Figure 6(a): Current V/s Time of PV Cell

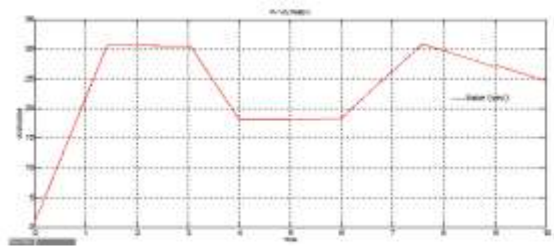

Figure 6(b): Voltage V/s Time of PV Cell

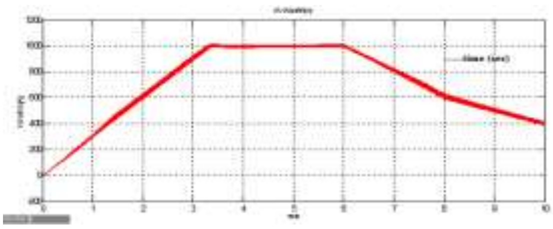

Figure 6(c): Power V/s Time of PV cell

Figure 6: Output values of current, voltage, power of PV cell

Fig 6 shows the output values of current, voltage and power of PV Cell. As it is clear from the output of above graphs of fig 6 that at t=0, current and voltage values are at lowest level i.e. 0, it is mainly due to no irradiance at that time and hence power is also 0. Now with time, irradiance level increases from (0 to 700W/m^2) & therefore, current & voltage also increases linearly with irradiance as shown in fig 6(a) & 6(b) and hence, its corresponding power also increases up to time period of 1.5 sec as shown in fig 6(c). After 1.5 sec irradiance level again increases from (700 to 1000W/m^2) due to which current increases continuously up to 3.5 sec. In the time interval of 3.5 sec to 4 sec irradiance levels decreases from (1000 to 600W/m^2) and after that it remains constant up to time period up to 6 sec, according to irradiance voltage & current becomes constant and hence its corresponding power also becomes constant. Similarly after 6 sec irradiance increases then decreases and this process continues up to a time period of 10 sec & accordingly the values of current and voltage changes linearly with time.

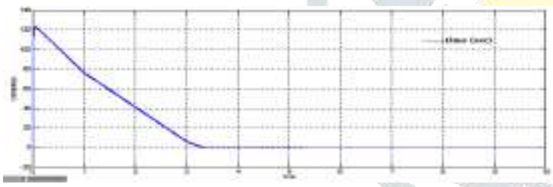

Figure 7(a): Current V/s Time of SC

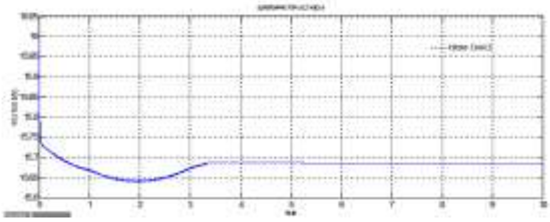

Figure 7(b): Voltage V/s Time of SC

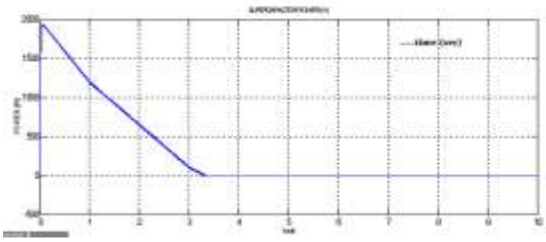

Figure 7(c): Power V/s Time of SC

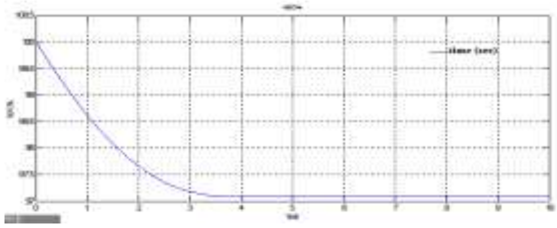

Figure 7(d): SOC% V/s Time of SC

Figure 7: Output values of current, voltage, power & SOC% of SC

Fig 7 shows the output values of current, voltage, power & SOC% (state of charge) of supercapacitor. As in the supercapacitor, the relation between the voltage and its capacitance is described as C=Q/V where Q represents charge stored in SC, C is Capacitance & V is Voltage of SC .Similarly the relation between the current & voltage is given by i = $\frac{dQ}{dt}$= $\frac{d(CV)}{dt}$= $c\frac{dV}{dt}$ and the discharging of supercapacitor can be determined by a expression i.e. V(t)= $V_O e^{-t/RC}$ where V(t) is a terminal voltage, Vo is output voltage , t is time and R& C are resistance and capacitance which is assumed to be constant.

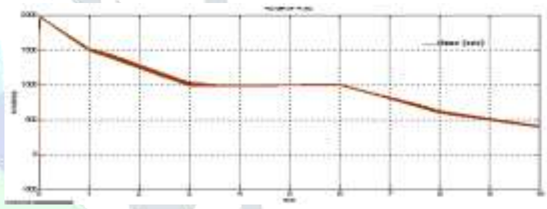

Figure 8(a): Power generated V/s Time by PV-SC

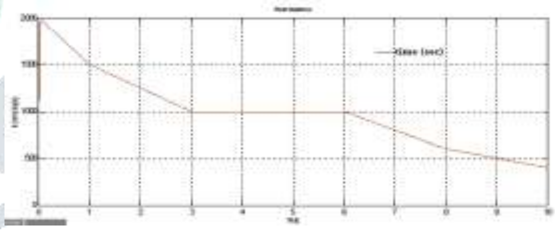

Fig 8(b): Power demanded V/s Time by load

Figure 8: Output power generated by PV-SC system & power demanded by load

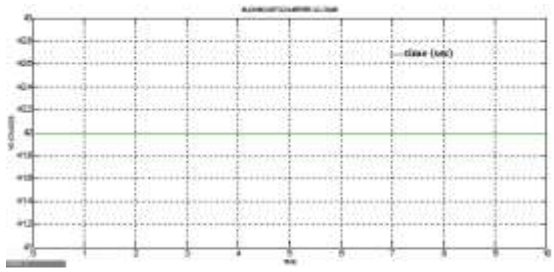

Figure 9: Voltage V/s Time of DC bus

Therefore, by using these expressions & graph output of fig 6 say that at t=0, SC was fully charged with its highest value of current and voltage i.e. 122 A &16 V respectively as shown in fig 7(a) & 7(b). Now with time, voltage of supercapacitor decreases exponentially & hence current also decreases due to which power of supercapacitor decreases or say that supercapacitor discharges with time up to time period of 3.5 sec as shown in fig 7(d). At 3.5 sec, current becomes saturated i.e. 0 and output voltage becomes constant at 15.6 V hence power becomes 0 as shown in fig 7(c). Fig 8 shows the output power generated by PV-SC system & power required by dc load. As it clear from the above graphs of figure 7 that power generated by system follows the power required by dc load. Here, generated power is equal to the sum of power generated by PV Cell as shown in fig 5(c) and power generated by SC as shown in fig 6(c) i.e.P_G =P_{pv}+P_{sc} . Fig 9 shows the output voltage V/s time graph of dc bus and it is clear from the graph that output voltage is continuous at 42 V.

V. CONCLUSION & FUTURE SCOPE

A sustainable energy system consisting of a photovoltaic cell with a supercapacitor to supply a non-grid connected load was introduced. From the results we concluded that designed hybrid photovoltaic-supercapacitor model was managed the power efficiently that during a transient load, PV provides the steady-state load and SC provides the transient load irrespective changes of irradiation with time. The impact of including the supercapacitor in the photovoltaic system was analyzed and the simulation results show the role of supercapacitor and PV for proper managing the power as per required by load. For future work, more than one energy storage device can be combined and MPPT tracker can be placed at the PV panels to obtain more efficient system to produce electricity.

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