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Storage Efficiency Optimization of an Ultracapacitor Charged By a Photovoltaic Cell Using Simulated Annealing

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ABSTRACT
Ultracapacitors are very power dense capacitors. Charge density of Ultracapacitors depends on the value of the capacitance and its voltage. Generally an Ultracapacitor with higher capacitance would support higher energy storage density with fixed voltage. The load driven often does not utilize properly the entire stored charge from the Ultracapacitor due to inconsistency in electrical characteristics between the load and source. Storage efficiency of Ultracapacitor has state of charge dependencies as it is variable over the duration of charge/discharge cycles. It depends directly on the capacitance and indirectly on the ESR value. The proposed optimization technique can significantly find the maximum value of storage efficiency at a near about minimum value of ESR and maximum value of capacitance. The simulation model and results shows the advantage of the said technique.

Keywords: Ultracapacitor, Photovoltaic panel, Simulated Annealing, Storage efficiency, Perturb & Observe algorithm.

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I. INTRODUCTION

Solar energy is one of the most widely available sources of renewable energy. It's abundance in availability and consistent supply from our sun makes it one of the most promising source of energy. It is the key to drive our future energy needs and also promote sustainable development. The most common technology used to tap this energy are photovoltaic (PV) cells [1]. Alternatives exists but photovoltaic being produced at mass scale reduces the cost of manufacturing. Photovoltaics have very low maintenance costs, they generate no pollution and there's almost zero greenhouse gas emissions. The efficiency of photovoltaic cells is low (10-25%), which can reach 35% and for this reason tracking of this incident sunlight is necessary in order to extract maximum power from the PV panels [2]. Many methods are present and one such efficient method is the Maximum Point tracking Algorithm (MPPT). As the insolation varies, the load characteristics that provide the best power transfer efficiency change, as a result maximum power extraction is affected.

MPPT keeps track of the changes in load characteristics to keep track of the maximum power point. Maximum power point trackers may employ various algorithm such as Incremental conductance, Perturb & Observe (P&O), Constant Voltage, Current sweep etc. Among the mentioned algorithms the P&O algorithm shows the best performance [3] [4]. MPPT algorithms change the Impedance of the circuit by employing DC-DC converters controlled by the MPPT controller so as to maximize the extraction of power from the PV panels to the load [5]. Load in most of the cases is usually a battery as they are the most widely used energy storage devices. However batteries take large time to store electrical energy in the form of chemical energy. Batteries also lack the ability to transfer power quickly to the load and cannot handle bursts of power in applications such as torque generation or regenerative braking in electric motors of electrical vehicles. To overcome such problems Ultracapacitors are used which are basically hybrid of capacitors and batteries. Unlike batteries they can charge or discharge energy at a very fast rate similar to a normal capacitor but their energy storage capacity is much larger compared to a normal capacitor similar to a battery. They have large charging and discharging cycles compared to rechargeable batteries. They generally use electrostatic double layer capacitance and electrochemical pseudo capacitance with variable contribution of each [6]. Ultracapacitor have large storage efficiencies and one of the most efficient storage devices. Storage efficiency of Ultracapacitors is generally a function of the internal resistance also called as equivalent series resistance (ESR) and the capacitance of the Ultracapacitor. The storage efficiency is directly proportional to the capacitance and inversely proportional to the internal resistance ESR. Our main area of interest in this paper is to find optimum values of ESR and Capacitance which would maximize the storage efficiency of the Ultracapacitor. In this work we have used Simulated Annealing which is an Artificial Intelligence based technique to optimize the values of ESR and Capacitance, so as to get the maximum possible efficiency.

The organization of this paper is as follows. In the next part (part II) a detailed description of the mathematical and electrical models used in the simulation is discussed and also the various algorithms used in these work. Part III verifies the facts and part IV provides the results obtained from our simulation and observation. Conclusion is given in Part V.

II. MATHEMATICAL MODELS AND ALGORITHMS

1. Model of the Photo-voltaic panel

Photovoltaic or solar cells are devices which are usually in the form of thin films or wafers, are semiconductor devices with large p-n junctions usually made of Si, that convert from 3-30% of incident solar energy to DC electricity, with efficiencies depending on illumination-spectrum intensity solar-cell design and materials and temperature. It generally behaves like a low-voltage battery whose charge is continuously replenished at a rate proportional to incident illumination. Connection of such cells into series-parallel configurations allows the design of solar 'panels' with high current and voltages.

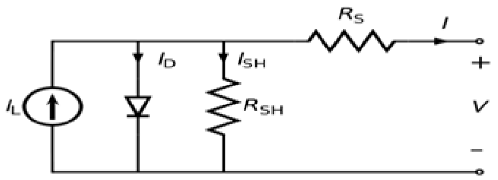

Fig. 1

From the circuit shown in *Fig. 1* it is evident that the current produced by the solar cell is [7] [8]:

$$I = I_L - I_D - I_{SH} \quad (1)$$

Where, I = Generated solar cell current, I_L= photo generated current, I_D= diode current, I_{SH}= shunt current.

The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S \quad (2)$$

Where, Vj = voltage across both diode and resistor R_{SH}, V = voltage across the output terminals, I = output current, R_S = series resistance.

According to Shockley diode equation [9], the current through the diode is

$$I_D = I_0 \left(e^{[V_j/nV_T]} - 1\right) \quad (3)$$

Where, I_0 = reverse saturation current, n = diode ideality factor, q = elementary charge, k = Boltzmann's constant, T = absolute temperature V_T the thermal voltage at 25°C, $V_T \approx 0.0259$ volt.

By Ohm's law, the current through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}} \quad (4)$$

Where, R_{SH}= shunt resistance. Substituting these into the first equation produces the characteristic equation of a solar cell i.e.

$$I = I_L - I_0\left\{e^{\left[\frac{V+IR_S}{\eta V_T}\right]} - 1\right\} - \frac{V+IR_{SH}}{R_{SH}} \quad (5)$$

Where R_S is not zero, the above equation does not give the current I directly, but it can then be solved using the Lambert W function:

$$I = \frac{(I_L+I_0) - V/R_{SH}}{1+R/R_{SH}} - \frac{\eta V_T}{R_S} W\left(\frac{I_0 R_S}{\eta V_T(1+R/R_{SH})} e^{\left(\frac{V}{\eta V_T}\left(1-\frac{R_S}{R_S+R_{SH}}\right)+\frac{(I_L+I_0)R_S}{\eta V_T(1+R_S/R_{SH})}\right)}\right) \quad (6)$$

When R_{SH} is infinite there is a solution for V for any I less than $I_L + I_0$:

$$V = \eta V_T \ln\left(\frac{I_L - I}{I_0} + 1\right) - IR_S \quad (7)$$

Otherwise one can solve for V using the Lambert W function:

$$V = (I_L + I_0)R_{SH} - I(R_S + R_{SH}) - \eta V_T W\left(\frac{I_0 R_{SH}}{\eta V_T} exp\left(\frac{(I_L + I_0 - I)R_{SH}}{\eta V_T}\right)\right) \quad (8)$$

The general form of the solution is a curve with I decreasing as V increases. The slope at small or negative V (where the W function is near zero) approaches, whereas the slope at high V approaches.

2. Output characteristics of the Photo-voltaic panel

When the cell is operated at open circuit, *I = 0* and the voltage across the output terminals is defined as the *open-circuit voltage*. Assuming the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is:

$$V \approx \eta V_T \ln\left(\frac{I_L}{I_0}+1\right) \quad (9)$$

Similarly, when the cell is operated at short circuit, the current *I* through the terminals is defined as the *short-circuit current*. The short circuit current I_{SC} is:

$$I_{SC} \approx I_L \quad (10)$$

It is not possible to extract any power from the device when operating at either open circuit or short circuit conditions. The output characteristics of the photovoltaic is shown in *Fig. 2*.

3. Simulation model of the Ultracapacitor

Ultracapacitor are usually double layered capacitor or DLC's and typically have very high capacitance value allowing them to store large quantities of electrical energy but the voltage remains low(maximum 3V) [10]. So, it helps to drive motor, pump and other mechanical devices which requires impulsive power. The energy stored in a Ultracapacitor is the product of half of the capacitance and the square of voltage, thus the more capacitance value is the distinguishing factor as the voltage which is fed to the system is almost constant for efficient charging and Ultracapacitors can charge/ discharge rapidly. Its small leakage current helps in long period of energy storage and the efficiency could exceed 95%.

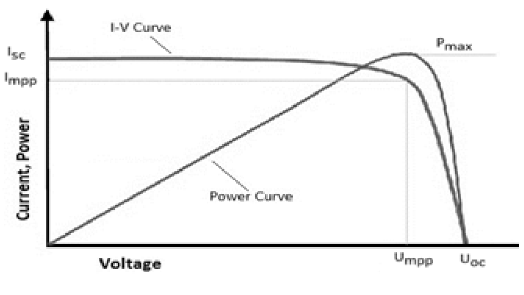

Fig. 2

In this paper we have used two resistance model of the Ultracapacitor for software simulation as shown in *Fig. 3*. Where, C_0 is a constant capacitor, R_1 is the equivalent series resistance and K_V*V is a voltage dependent capacitor and this first branch models the voltage dependencies of the Ultracapacitor. The second branch consisting of R_2 and C_2 are responsible for taking into account the charge redistribution taking place within the Ultracapacitor. The Resistance R_3 is called the equivalent parallel resistor and is used to model the leakage behaviour of capacitor. The Ultracapacitor has an inherent tendency of reduction in storage efficiency with increase in the value of ESR and the slope of the curve changes with higher values of ESR. The storage efficiency is also a function of capacitance and with increasing value of capacitance the storage efficiency of the Ultracapacitor increases and the slope of the curve keeps on decreasing as the capacitance reaches higher and higher values.

4. Simulation model of the buck Converter

The buck converter or step down converter is basically a switched mode DC-DC power converter which can transfer packets of energy from its input to output depending on the frequency of the switching signal applied to the switch S, which in most cases is usually a power transistor such as MOSFET whose gate is used to control the switching action. Buck converters in most cases could be very efficient and can provide efficiencies more than 90%.Matlab model of the buck converter used in our simulation is shown in *Fig. 5* and the corresponding equivalent electrical circuit is shown in *Fig. 4*.

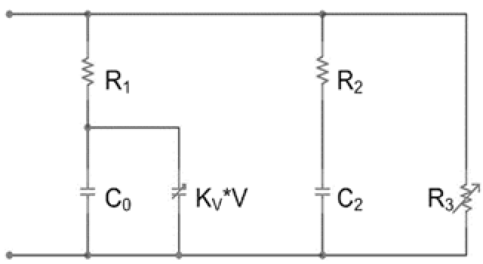

Fig. 3

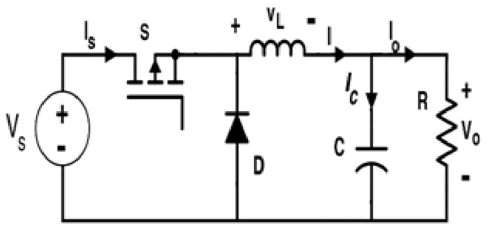

Fig. 4

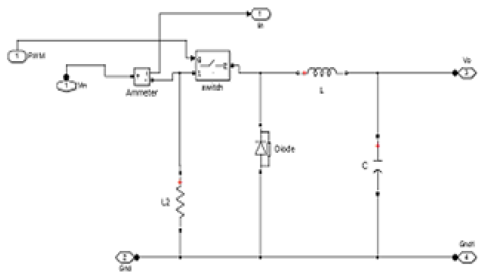

Fig. 5

5. Application of Maximum Power Point Tracking for efficient power delivery to Load

In our simulation in order to maximise the power delivery from PV panel to the Ultracapacitor we have used the Maximum power point tracking algorithm or MPPT. Maximum power point tracking algorithm is a tracking algorithm usually employed to maximize the output power to loads from photovoltaic panels. Different MPPT algorithms such as Perturb and Observe, Incremental Conductance etc. try to find out the point from the P-V characteristics of the solar panel where the power delivered by the panel is maximum. Out of many available MPPT algorithm P&O or Perturb and Observe algorithm appears to be most promising with better tracking efficiency. The P&O algorithm flowchart is shown in *Fig. 6*.

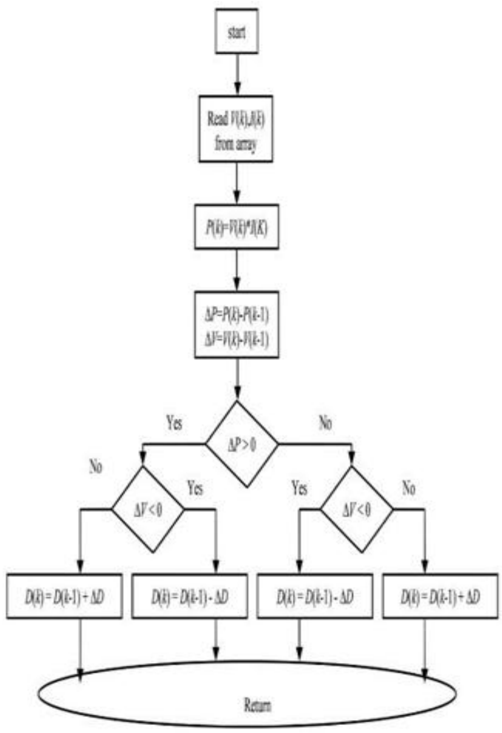

Fig. 6

Mathematical model [11] of the Perturb and Observe algorithm used in the model is shown in *Fig. 7*.

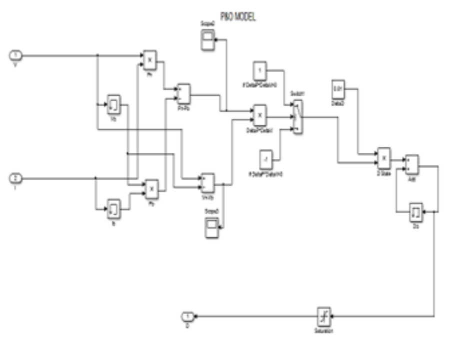

Fig. 7

6. Complete simulation setup of the system

The complete simulation setup is shown in *Fig. 8*.

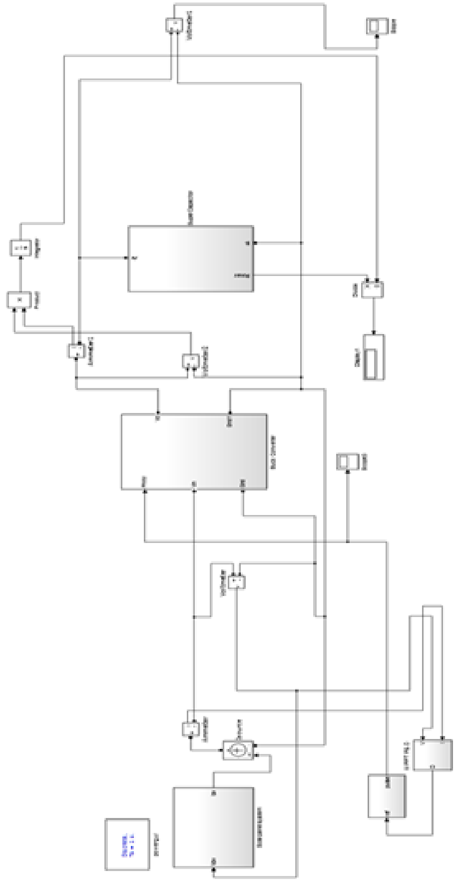

Fig. 8

7. Simulated Annealing:

Annealing process in metallurgy means metals are cooled to make them achieve a state of low energy for solidification and strength. Simulated annealing is an analogous method for optimization where the temperature is reduced slowly, starting from a random search at high temperature eventually becoming pure greedy descent as it approaches zero temperature [12]. Greedy descent leads to local minima and randomness helps to escape of the local minima and find regions having low heuristic values. Simulated annealing algorithm picks variable and value at random. When initializing the temperature variable, selection of a certain temperature will initially allow for practically any move against the present solution. This helps in better optimization. In comparison to the hill-climbing technique the simulated annealing algorithm does not get stuck at the local maxima and therefore searches the entire curve for global maxima.

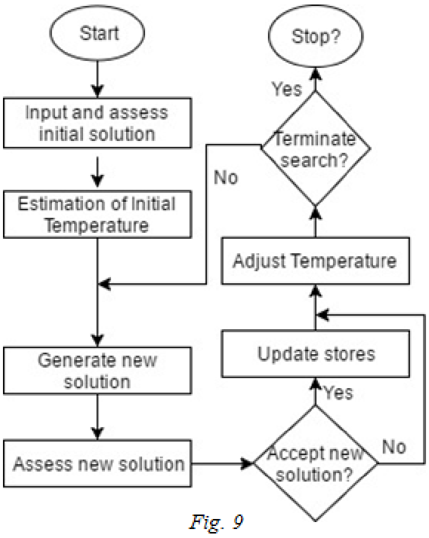

Fig. 9

III. VERIFICATION OF THE VARIATION IN STORAGE EFFICIENCY WITH ESR AND CAPACITANCE

We have simulated the model and tried to verify the storage efficiency variations with variation in ESR and capacitance. The response of storage efficiency vs. ESR obtained from the model is shown in *Fig. 10*.The response of storage efficiency vs. Capacitance obtained from the model is shown in *Fig.11*. The 3D plot with axes as efficiency, ESR and Capacitance obtained after extrapolation of the sample data obtained from the model is shown in *Fig.12*. It can be observed from *Fig. 10, Fig. 11* and *Fig. 12* that the fact that storage efficiency increases with decrease in ESR and increase in capacitance of Ultracapacitor.

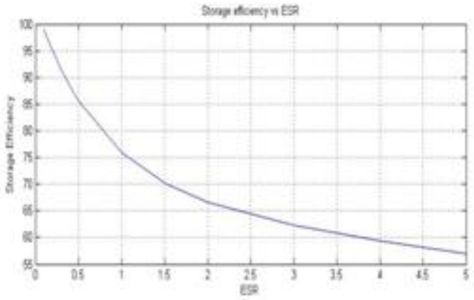

Fig. 10

Fig. 11

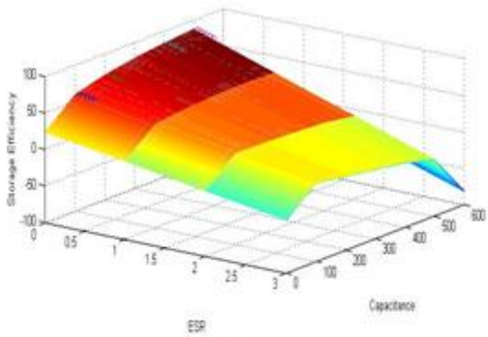

Fig. 12

IV. EXPERIMENTAL RESULTS

The simulation of the model was done to get enough sample points for further processing by the Simulated Annealing. At first the model was used to determine the variation in efficiency with variation in ESR and Capacitance individually and independently and the data points were plotted as shown in the graphs in Part III. These sample data points were then used to find the polynomial function which will eventually be modified and used as a fitness function in Simulated Annealing. The data points observed from the model are given in table 1.

Table 1

ESR(ohm)	Capacitance (Farad)	Storage efficiency (%)
0.05	100	58.63
	200	69.26
	300	76.83
	400	81.37
	500	85.06
0.1	100	57.45
	200	67.88
	300	74.69
	400	79.45
	500	82.96
0.15	100	56.52
	200	66.58
	300	73.11
	400	77.66
	500	81
0.2	100	55.64
	200	65.37
	300	71.64

	400	75.99
	500	79.18
0.25	100	54.82
	200	64.22
	300	70.26
	400	74.43
	500	77.48

Further this data have been used to get the polynomial function using the Curve fitting toolbox of MATLAB. The obtained polynomial is of order 2 as given in (11).

$$z(x,y) = p_{00} + p_{10}x + p_{01}y + p_{20}x^2 + p_{11}xy + p_{02}y^2 \quad (11)$$

Where, x is the equivalent series resistance (ESR) and y is the capacitance of the Ultracapacitor and p00 = 47.79, p10 = -20.41, p01 = 0.1339, p20 = 19.6, p11 = -0.04914 and p02 = -0.0001104 are coefficients of (11).

We have used (11) in simulated annealing for optimization of the efficiency since the stimulated tool in MATLAB is configured for data minimization we have used fitness function f(x,y) given as (12), so that minimization of f(x,y) will lead us to maximization of z(x,y) which is essentially the overall efficiency.

$$f(x,y) = {}^{1}/_{z(x,y)} \quad (12)$$

Final data obtained after optimization by simulated annealing algorithm at different Initial temperatures is given in Table 2.

Table. 2

Initial Temperature	ESR (ohm)	Capacitance (Farad)	Storage Efficiency (%)
10	1E-003	982.15	73.68
20	0	964.79	74.81
30	7E-003	963.77	76.4
40	0	948.5	77.89
50	0	833.05	82.71
60	2E-003	818.18	83.34
70	8E-003	779.37	84.59
80	1E-003	884.6	79.77
90	1E-003	701.82	87
100	0	620.25	88.36

II.

Final data obtained after optimization by simulated annealing algorithm at constant Initial temperature of 100 and different Re-annealing intervals is given in Table 3.

Table. 3

Re-annealing Interval	ESR (ohm)	Capacitance (Farad)	Storage Efficiency (%)
10	1E-003	597.99	88.34
20	2E-003	667.01	87.86
30	0	598.19	88.36
40	0	665.64	88
50	0	658.18	88.08
60	2E-003	611.05	88.29
70	0	636.49	88.29
80	1E-003	609.23	88.35
90	3E-003	793.33	84.32
100	4E-003	800.61	84.02

V. CONCLUSION

In conclusion, it should be clearly emphasized that a lower value of ESR and high Capacitance is desired for better storage efficiency. The initial results shows that typical storage of efficiencies greater than 88% can be obtained at the above obtained values of ESR and capacitance with little or no changes in Re-annealing interval but the efficiency varies a lot with variations in Initial temperature of the algorithm. This method explores the area of implementation of AI computing techniques in optimization of Ultracapacitor performance. When compared with storage efficiencies optimized by Genetic algorithm [13] [14] it can be easily observed that simulated annealing gives better storage efficiency optimization at higher Initial temperatures and therefore can be effectively used for optimization.

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