PV Output Power Smoothing Using Energy Capacitor System

Arash Jamehbozorg, Seyed Nasser Keshmiri, *Student Member, IEEE*, and Ghadir Radman, *Senior Member, IEEE*

Abstract **– Photovoltaic systems are being considered as one of the major sources of electrical energy for next decades. The cost of PV cells is decreasing more and more and this will help increase its penetration in power systems. One of the main issues of PV systems is their dependency on irradiance of the sun and temperature of the cells. As during day-time both these factors are changing continuously, the output power of PV cells would have considerable fluctuations that would not be acceptable in power systems with high penetration of PVs. In order to solve this problem, this paper proposes a system to smooth the output power of the PV using Energy Capacitor System. A case study for investigating the performance of the proposed configuration is simulated and results show that it can considerably smooth the output power of the PV system.**

Index Terms **– Photovoltaic Cells, MPPT System, Energy Capacitor System, Output Power Smoothing.**

I. Nomenclature

I – Output current of the PV cell [A],
I_{pv} – Current generated by the incident light [A],
I_0 – Reverse saturation current of the diode [A],
V – Output voltage of the PV cell [V],
R_S– Series resistance of the PV model [Ω],
R_{Sh}– Shunt resistance of the PV model [Ω],
a– Ideality factor,
$I_{0,ref}$– Nominal saturation current [A],
T– Temperature of the PV cell [K],
T_n– Nominal temperature [K],
ε– Material band gap energy [eV],
a_{ref}– Nominal ideality factor of the PV cell [K],
V_{OC}– Open circuit of the PV module [V],
V_t– Thermal voltage [V],
N_S– Number of series cells,
K– Boltzmann constant = 1.38×10^{-23} [J/K],
q– Electron charge = 1.6×10^{-19} [C],
I_{SC}– Short circuit current of the PV [A],
k_i– Short circuit current/temperature coefficient [A/K],
G– Irradiance of the sun [W/m^2],
G_n– Nominal irradiance of the sun [W/m^2].

II. Introduction

PENETRATION of green sources of electrical energy in power system is rapidly increasing in last decade. The rising of the fossil fuels cost and tendency toward decreasing the pollution caused by conventional power plants are two major reasons for this increased attention. Among all of the renewable technologies, Photovoltaic (PV) is the fastest growing renewable energy in the world with 50% annual increases cumulative in installed capacity in 2006 and 2007 [1]. The total capacity of PV cells installed is estimated to be around 10.7 GW at the end of 2009. USA has been ranked 5th in the world by producing 587 MW using PV in 2009. It is expected that this number would be increased to 3-6 GW in 2014 [2].

PV systems need Maximum Power Point Tracking (MPPT) modules because of their V-I characteristics. This module increases the efficiency of the PV systems noticeably. Several authors investigated PV-characteristics and proposed different MPPT techniques ([3]-[9]).

One of the main problems of the PV (in addition to its high production cost) is that, the output current of the PV cells is highly dependent to the irradiance of the sun and temperature of the cell. This will cause some fluctuations in the output power and voltage of the PV cell. This situation is not acceptable in power system especially in a system with high penetration of PV systems.

This paper proposes the use of Energy Capacitor System (ECS) in parallel with PV module to smooth the output power of the PV. By decreasing the cost of producing super capacitors, utilizing ECS in power system is growing. ECS can deliver power to the system very fast. The super capacitors are capable of working while there is continuous switching of the DC/DC converter of the ECS, without losing their performance considerably. In the next section the modeling of different parts of the proposed system would be presented. Then the proposed configuration for using ECS with PV would be introduced and then using a case study the performance of the configuration would be investigated. PSCAD software [10] is used for implementing the system.

III. Modeling of the System

The proposed configuration has three different components.

The electrical model of each of them is as follows.

A. PV Cell

The schematic diagram of the PV cell model is shown in Figure 1. Basic formula of PV is [11]:

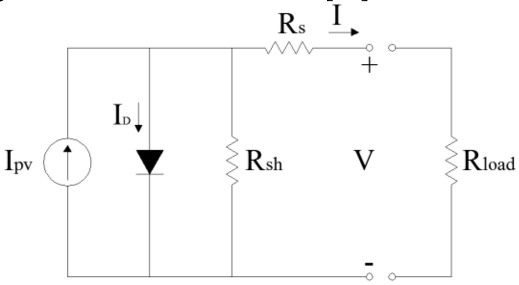

Figure 1 – Schematic diagram of the PV model

$$I = I_{pv} - I_0\left[e^{\frac{V+IR_S}{a}} - 1\right] - \frac{V+IR_S}{R_{sh}} \quad (1).$$

Where

$$I_0 = I_{0,ref}\left(\frac{T}{T_n}\right)^3 . e^{\frac{\varepsilon N_S}{a_{ref}}\left(1-\frac{T_{ref}}{T}\right)} \quad (2)$$

$$a = \frac{T}{T_{ref}} a_{ref} \quad (3).$$

Also,

$$I_{0,ref} = \frac{I_{sc}}{e^{\frac{V_{oc}}{aV_t}}-1} \quad (4),$$

$$V_t = \frac{N_S KT}{q} \quad (5),$$

$$I_{pv} = \left[I_{sc} + k_i\left(T - T_{ref}\right)\right]\frac{G}{G_n} \quad (6).$$

As it can be seen the output current of the PV cell is dependent to irradiance of the sun and the temperature of the cells. Figure 2 and Figure 3 show the V-I characteristic of the PV for different irradiances and temperatures, respectively.

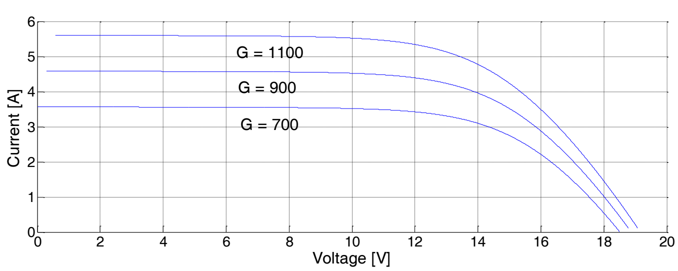

Figure 2 – V-I characteristics for three different values of irradiances

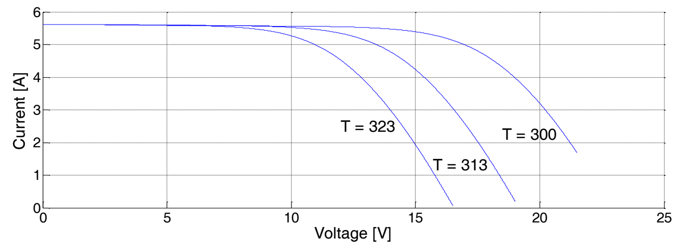

Figure 3 - V-I characteristics for three different values of temperatures

B. MPPT System

When a photovoltaic unit is connected to a load, the operating point of photovoltaic unit is determined by the intersecting of the I-V characteristics of PV module and load, which is called load line. Generally speaking, this operating point rarely happens to be at the PV module's maximum possible producing power. For example from Figure 2 it can be inferred that the power of the PV cell is maximum when $V = 13.67\,V$ and $I = 4.07\,A$ (while $G = 900\frac{w}{m^2}$). It means that the resistance that can be seen from the cell should be $\frac{V}{I} = 3.36\,\Omega$. But, the problem is that the load is fixed and is not under our control, thus it is possible that it would not be even near the optimum resistance. It means that the output power of the PV would be so much less than its nominal value. Therefore, in order to solve this issue, a MPPT module can be applied to sustain the PV module operating point at Maximum Power Point.

Nowadays, Maximum power point tracker systems play an important role in photovoltaic systems; they maximize the power output from a PV system for any given set of conditions, maximize the array efficiency, and therefore minimize the overall system cost. MPPT systems find and sustain operating point at the maximum possible power point, using an MPPT algorithm. Many different algorithms have been proposed in literature ([3]-[9]). Some of the well-known algorithms are: perturb-and-observe (P&O) method, Ripple-based extremum seeking, Constant voltage and current, Pilot Cell, Incremental Conductance, Parasitic Capacitance, etc. In a specific irradiance and temperature, the output power of the PV cell can vary from zero to a maximum value based on the load.

In this paper a Hill Top algorithm [12] is used for MPPT purpose. The flow chart of the algorithm is shown in Figure 4. In each step, after sensing voltage and current of the PV cell, by comparing them with the previous value of the output power, the duty cycle of the Insulated-Gate Bipolar Transistor (IGBT) would be changed. If the power has been decreased the duty cycle would be increased and vice versa.

Finally, this duty cycle is compared with a triangle waveform to generate the switching signal of the IGBT.

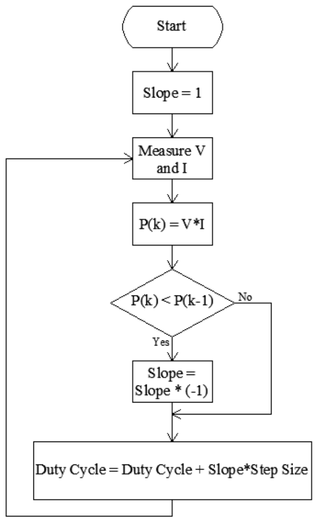

Figure 4 – Flow chart of Top-Hill algorithm

C. ECS Model

One of the most attractive solutions that applied for smoothing the output power is Electric Double-Layer Capacitor (EDLC) system. The EDLC consists of two activated porous carbon electrodes. EDLC has the advantages of virtually unlimited life cycle, fast charging time, simple charging method, not having any harmful materials for environment and not needing a protective circuit. Also, over-charging or over-discharging does not harm the EDLC [13].

The ECS consists of EDLC and a DC-DC buck-boost converter. There are several models presented for ECS in different literatures. In this paper the model showed in Figure 5 is used for ECS.

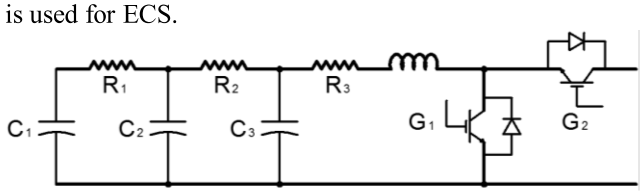
Figure 5 – Distributed model of the EDLC

Formulas for designing the EDLC based on the desired power and energy of the EDLC can be found in [13].

The buck-boost converter controls the power exchange between EDLC and the PV cell. When the actual power is less than the reference power, power will be injected to the DC-link by switching of G_1 while G_2 is turned off at all time. In charging mode, i.e. when the actual power is more than the reference power, the EDLC will be charged through switching of the G_2 while G_1 is turned off. Block diagram of the DC-DC converter is shown in Figure 6.

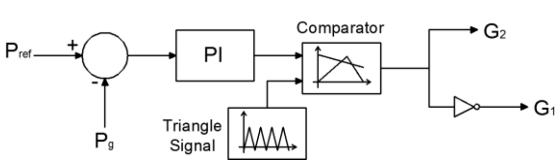

Figure 6 – Block diagram of the DC-DC buck-boost converter controller

IV. PV Output Power Smoothing Using ECS

As described in previous section, the output current of the PV cell is dependent to the irradiance and the temperature. So, during the day the output power of the PV cell would have some fluctuations and the magnitude of these fluctuations is dependent on the changes in the irradiance and temperature. This situation is not acceptable in the power system, especially if the PV cell is feeding a micro grid. For solving this problem ECS can be placed in parallel with the PV cell so that the power of the entire system is smoothed. The configuration of the proposed system is shown in Figure 7.

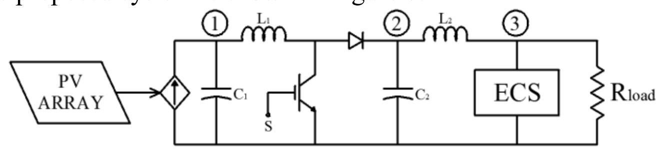

Figure 7 – Schematic of the proposed system

V. Simulation Results

For investigating the performance of the proposed system a case study has been implemented using PSCAD software. The parameters of the different parts of the system are given in Appendix A.

First, a case with constant irradiance and temperature has been simulated. The results of the simulation are shown in Figure 8 to Figure 12. As seen the MPPT switches the IGBT so that the resistance of the load (100 Ω in this simulation) is seen as, approximately, a 3.2 Ω load. So, the injected power to the load is increased to 45 W.

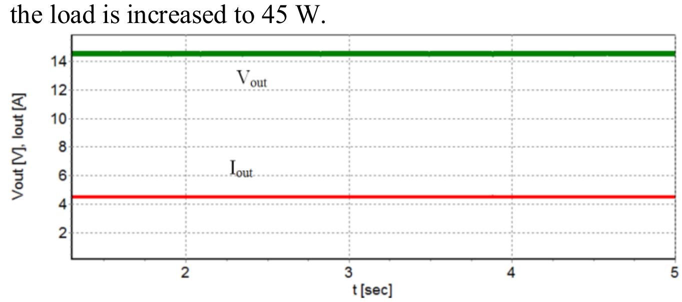

Figure 8 – Output voltage and current of the PV cell at node 1

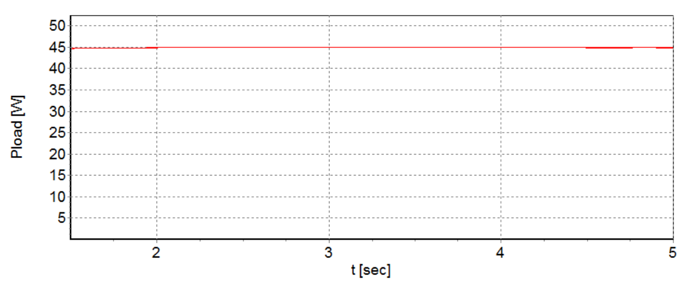

Figure 9 – Injected power at node 3

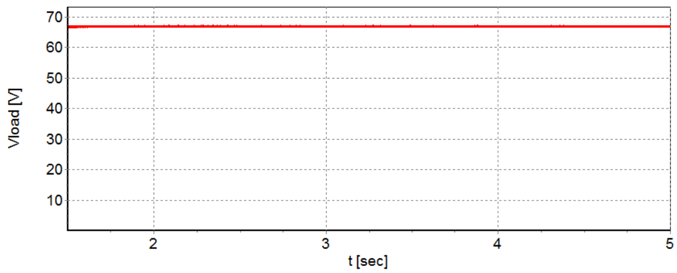

Figure 10 – Load voltage (node 3)

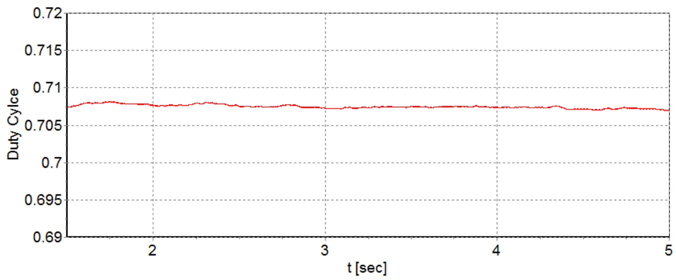

Figure 11 – Duty cycle of the MPPT module

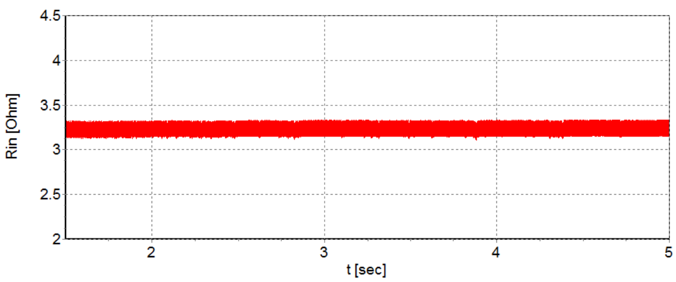

Figure 12 – V/I ratio measured at node 1

In next case, variable irradiance (shown in Figure 13) is used instead of a constant value. The output power of the PV cell in this condition (without applying ECS) is shown in Figure 14. The fluctuations of the output power are about 15 W (33.33%).

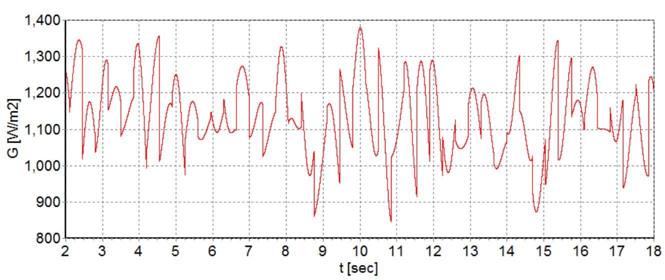

Figure 13 – Variations of the irradiance

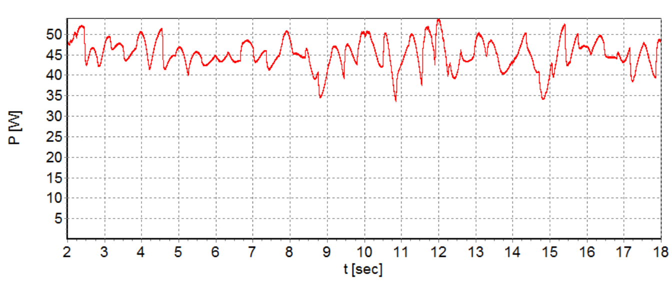

Figure 14 – Injected power to the load at node 3 (without using ECS)

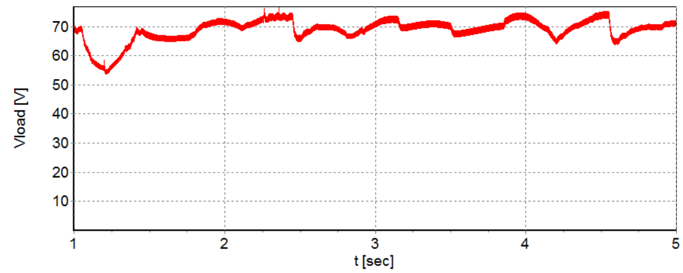

Figure 15 – Voltage at node 3

Then, the ECS is applied in the system to smooth the power. The results of the simulation in this case are shown in Figure 16 to Figure 19.

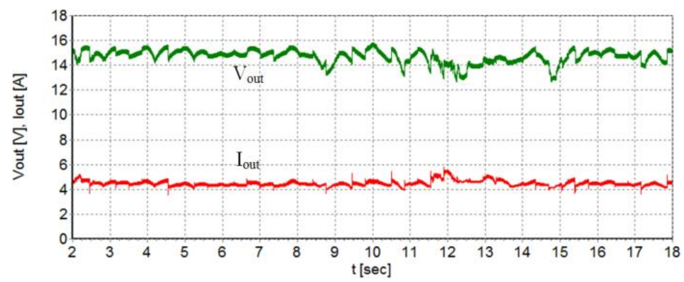

Figure 16 – Voltage and current of the PV with variable irradiance

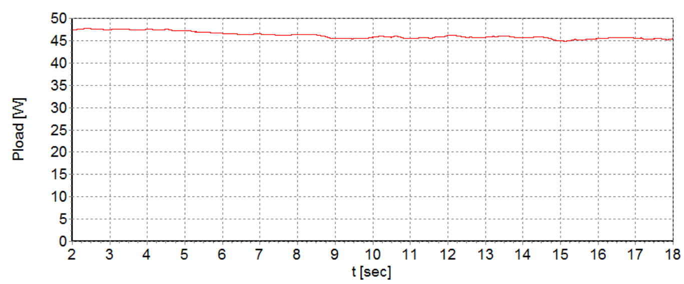

Figure 17 – Power injected to the load at node 3 (including ECS)

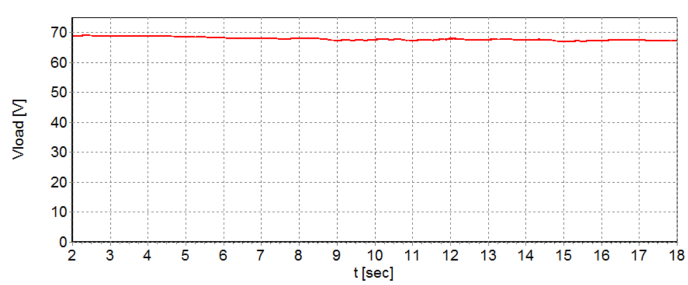

Figure 18 – Voltage at node 3 after using ECS

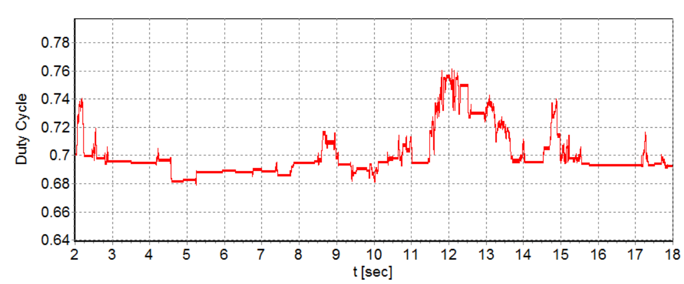

Figure 19 – Duty cycle of the MPPT module

As seen, the fluctuations of the output power is very small after using ECS (less than 5 W or 11.11%). Also, the ECS reduces the variations of the load voltage significantly.

VI. CONCLUSION

Because of the dependency of output power of the PV cells to the irradiance and temperature, noticeable amount of fluctuations is injected to the system that is not acceptable and should be reduced so that the power quality of the system is improved.

In this paper application of the ECS for smoothing the output power of the PV cells has been investigated. By storing the power when the output power of the PV cell is more than the reference power and discharging it when the output power is less than the reference value, the smoothing process has been performed using ECS. The models of the PV cell, MPPT module and ECS have been presented. Using a case study the performance of the proposed system has been studied.

Simulation results show that this system can smooth the output power of the system considerably. Also, it helps reduce voltage fluctuations drastically.

VII. APPENDIX A

The parameters of the PV cell and ECS are given in Table 1 and Table 2, respectively.

Table 1 – Parameters of the PV cell

Parameter	Value
I_{SC}	5.078 A
V_{OC}	21.827 V
k_i	1.141e-3 A/K
N_S	36
R_S	0.502 Ω
R_{Sh}	644.13 Ω
T_n	297 K
G_n	1000
ε	1.2
a	1.5

Table 2 – Parameters of the ECS

Parameter	Value
R_1	0.75 Ω
R_2	0.78125 Ω
R_3	0.03125 Ω
C_1	40.32 mF
C_2	42 mF
C_3	1.68 mF

VIII. ACKNOWLEDGMENT

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X. BIOGRAPHIES

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