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Impact of Dynamic PHEV Load On Photovoltaic System

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ABSTRACT

This paper presents the dynamics of photovoltaic (PV) cell with Plug in Hybrid Electric Vehicles (PHEVs) load. It is expected that PHEVs are going to be charged during the day from solar PV energy sources at their parking sites. The present work offers a complete system for charging PHEVs using PV cell where PHEVs load are modelled based on a third order battery model. The system dynamics are analyzed at the maximum power point (MMP) while Perturb and Observe (P&O) method is used to ensure the tracking of MMP from the PV cell. Impacts of PHEV loads on the dynamic behavior of a solar power system under both small disturbance and large change in radiation have been investigated in this paper. Simulation results demonstrate that it is important to consider the dynamics of PHEVs load for charging using PV cell.

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1. INTRODUCTION

Plug in Hybrid Electrical Vehicles (PHEVs) could be a strong alternative to the conventional vehicle. It is expected that in the future a majority of vehicles will have a plug-in option for recharging their batteries. It is a challenge for power system engineers to ensure a continuous power supply to allow PHEVs to be fully charged. As the existing power systems in most countries have limited energy resources, researchers are working towards the proper management of energy (such as charging at night), as well as alternative sources like wind energy, biomass and solar energy. Several research works have been carried out and some are still on going to implement the recharging of PHEVs using PV cell, as it is a clean source of energy with zero carbon emission. However the dynamics of PV cell and PHEV have not been considered together in the literature.

A PHEV should be a logical choice for a car user due to advances in battery and hybrid-electric power technologies, coupled with its financial, energy security and environmental advantages and the rising costs of petroleum [1]-[3]. PHEVs can be charged directly from a domestic power connection from the grid as well as renewable energies, incur much lower fuel bills and have the flexibility to stor wind and solar energy at times of excess power generation. PHEVs have the potential to revolutionize not only how we drive but how we generate and use electricity in our homes and workplaces. Currently researchers are working on, how householders can charge their cars from solar panels on their rooves which could dramatically reduce greenhouse gas emissions.

A PV energy system is one of the cleanest power-generating technologies available today and has very little impact on the environment. When it operates, it converts the sun's rays into electricity and, produces no air pollution, waste, or noise. The greater use of PV energy to generate electricity from the sun's rays decreases our dependence on fossil fuels and imported sources of energy. As a result, solar energy can be an effective driver of economic development. The world PV market installations reached a record high of 7.3 gigawatt (GW) in 2009, representing a growth of 20% over the previous year [4].

It is expected that by the year 2020, PHEV penetration will be 25% which represents a large additional load on power systems [5]. According to the Electric Power Research Institute (EPRI), PHEVs will be recharged during overnight off-peak hours when total electricity generation in the U.S.A. reduces by 60% whereas if 50% of all road vehicles are replaced by PHEVs by the year 2050, this generation will need to be increased by 8% to fulfil the demand [6] which may produce large and unexpected peaks in power consumption. However through dmand management or using alternative renewable energy sources such as solar, charging PHEVs during off-peak, or even peak times might be possible [7, 8] as solar energy could be used to charge PHEVs during the day when numbers of cars are garaged in various office car parks.

However, the load management of power system may not be so simple with increasing penetration levesl of PHEVs as many networks do not have sufficient spare capacity [9]. Since many distribution systems were designed decades ago considering the load levels at that time, they might require some changes due to the new load levels, patterns and load characteristics [9, 10]. Therefore, it is very important to identify the effect of a specific load on the stability and control of power system. In this situation the impact of charging PHEVs with PV cell has been analysed in this paper with a complete dynamic load model.

Although a few studies have been conducted on the load levels and cost benefit analyses of PHEV penetrations in power systems [11]-[12], the effects of PHEV battery charging on PV cell due to their dynamic load characteristics has not been studied so far. This paper consider the dynamics of a vehicle charging system and battery, to represent the dynamic PHEVs model and make an analysis for the stability of PV cell systems with PHEVs as dynamic loads.

The organisation of this paper is as follows. Section 2 presents the modelling of the PHEV; Section 3 provides the PV generator model; Section 4 provides the mathematical model; in Section 5 linearization of the state equation is considered of the overall system; in Section 6 small-signal analysis is presented to understand the impact; and Section 7 presents the conclusions.

2. LOAD MODELING

To connect a PHEV with an electrical distribution system for battery charging, an electronic interface is required [14]. Along with the dynamic responses of the electrolyte temperature and battery's state-of-charge (SOC), the effect of the electronic rectifier or charger is considered to model the load. Till today lead-acid and nickel-cadmium types of batteries have been the most common for electric vehicles [15].

On an average, more than 50% of cars in the U.S.A are driven about 25 miles per day [7]. To evaluate the impact of PHEVs we consider a driving range of 40 miles/day, which means that the capacity of a PHEV battery will be 12 kWh as 0.3 kWh of its battery energy is required to drive one mile [9], [11]. The practical data available from the advanced research vehicle as shown in Figure 1 [13] is used in this work. This vehicle specification is exactly same with the calculated load model.

Vehicle Specification

Model	Escape 2010 Ford
Output	155hp @6000 rpm, 2.5 L
Battery	Lithium-Ion

Electric Drive and Charge System

No. of cell	84
Cell voltage	3.6 V
System Voltage	302 V
Charging Voltage	120 V
Charging Current	30 A
Charger power	3.6 kW
Pack Energy	12 kWh

Figure 1. 2010 Ford Escape [13]

A dynamic model of a battery [16], [17] is selected to develop a suitable model of PHEV load, in which the elements of the load are not constant as they depend on the electrolyte temperature and batery's state-of-charge (SOC).

The battery equivalent network represented in Figure 2, where θ represents the electrolyte temperature, SOC is the battery's state-of-charge. I_m an integral part of the total current (I) used to store charge in the battery. Another part of the total current entering the battery flows through the parasitic branch. Parasitic reaction is a continuous process that draws current but does not participate in the main reaction.

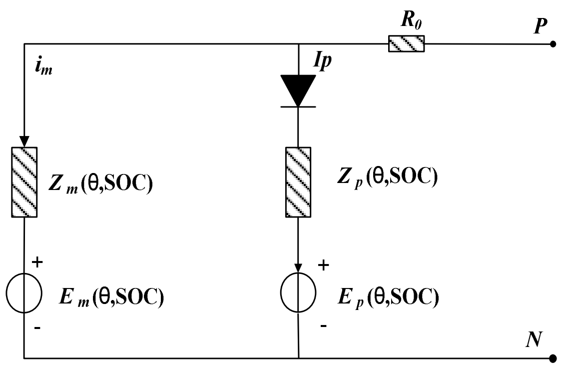

Figure 2. Battery equivalent network with parasitic branch

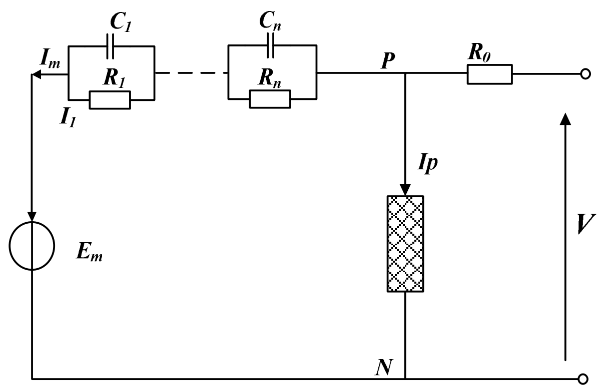

Figure 3. Battery equivalent network

The voltage at this branch is nearly equal to the voltage at the pin. The power dissipated in real part of impedance Z_m for charg and parasitic part Z_p is converted into heat. The impedance of the main reaction branch increases with an increasing charge, which causes the terminal voltage of the parasitic branch rise and the current I_p to rise and a full state of battery charge, it approaches infinity [16]- [21].

This battery model can be represented as an RLC network as illustrated in Figure. 3 and the number of R-L-C blocks can be kept limited as the specific speeds of evolution of the electrical quantities evolve very rapidly for PHEVs [16], [17]. The parameters used for the battery are given in Appendix A.

Finally this model is integrated with a PV cell to investigate the impact of PHEVs load, shown in Figure.5.

3. PV GENERATOR MODEL AND CONTROLLER

A current source anti-parallel to a diode is the simplest representation of an electrical equivalent circuit for a solar cell and is shown in Figure 4. The Kirchhoff's law gives

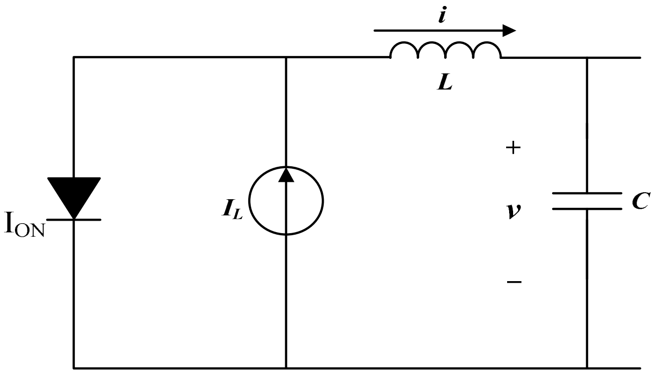

Figure 4. PV equivalent circuit [22]

$$I_L - I_s\{\exp[\alpha(v + L\frac{di}{dt})] - 1\} - i = 0 \tag{1}$$

where $\alpha = q/nsKT$, $q = 1.6022\times10^{-19}$ is the charge of the electron, $K = 1.3807\times10^{-23}$ J/K the Boltzman's constant, $T = 298K$ the temperature and ns is the number of series cells in the array. However the inputs to the solar PV are the solar radiance $[W/m^2]$, temperature $[^0C]$, and PV voltage [V] while the only output is the PV current supplied by Panel [A]. Therefore the output current can be characterized by $I = f(V)$.

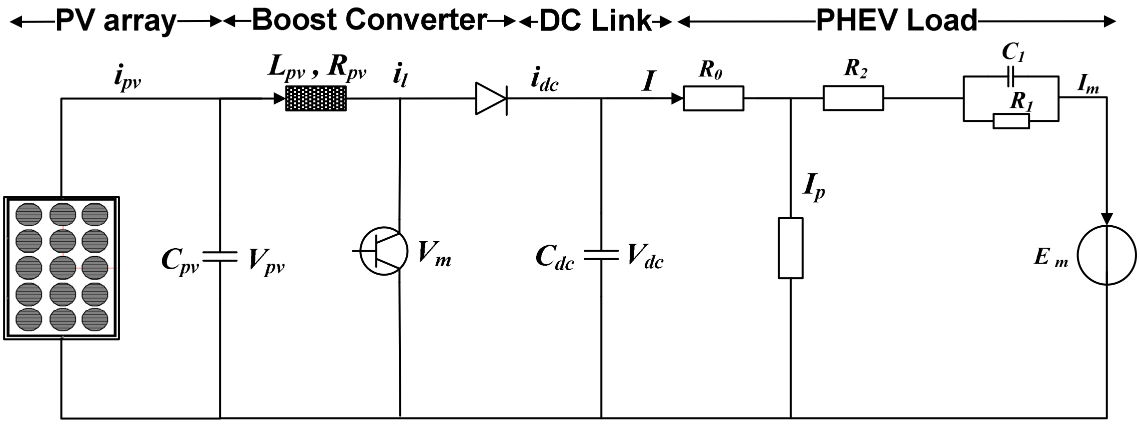

Figure 5. General diagram of the system [23], [24]

As PV power varies with climatic conditions, there is no explicit reference power for tuning. Therefore, the PV voltage needs to be adjusted according to the solar radiation to extract the maximum PV current. With regulation of the generator voltage (V_{pv}) and inductor current (I_l) and by varying the transistor's cyclic ratio this adjustment is possible. The regulator measures the PV voltage and current using an intelligent algorithm between the PV array and load as a MPP tracker (MPPT), which ensures the operation of the PV at its MPP. In this work, the Perturb and Observe method (P&O) [25] - [26] chosen for obtaining the MPP, then finds the adequate voltage (V_{pv}^*) which the boost converter imposes on the system. The reference voltage is determined by the calculation of the two adequate controllers and two compensators shown in Figure 6.

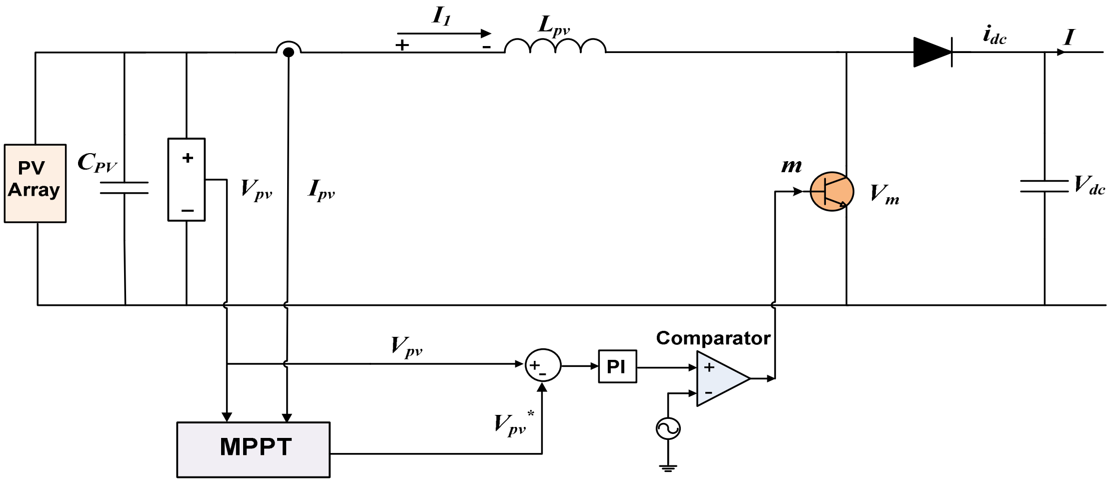

Figure 6. PV converter controller System

The voltage and current in the capacitor (C_{pv}) and inductance (L_{pv}) respectively give optimal command of the current and voltage. The voltage control loop with the PV current compensation gives the current reference (I_l^*) and the current control loop with the PV voltage compensation gives the voltage reference (V_{pv}^{*}). The controller parameters are chosen to maintain a constant PV voltage and minimize the current ripple.

This PV cell model is implemented in PSCAD for nonlinear simulations, where the PV array is interfaced as a nonlinear current source.

PV energy has radiation and temperature dependent nonlinear P-V characteristic. To utilize the maximum amount of energy from a PV cell, it is important to track its MPP which varies with changing atmospheric conditions. Generally its maximum power output occurs around the knee point of the P-V curve as shown in Figure 7.

In this work the P&O method has been chosen for obtaining MPP, as shown in Figure 8 and implemented in PSCAD, due to its simplicity and low computational demand [25].

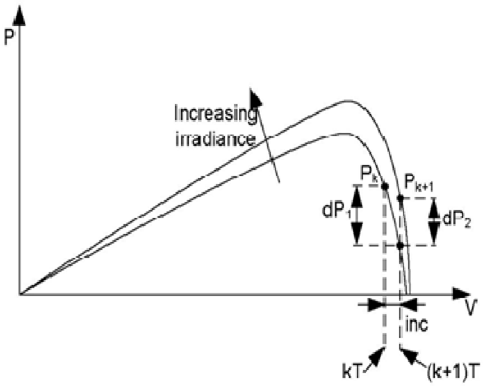

Figure7. P-V characteristic curve of PV cell with MMP T [26]

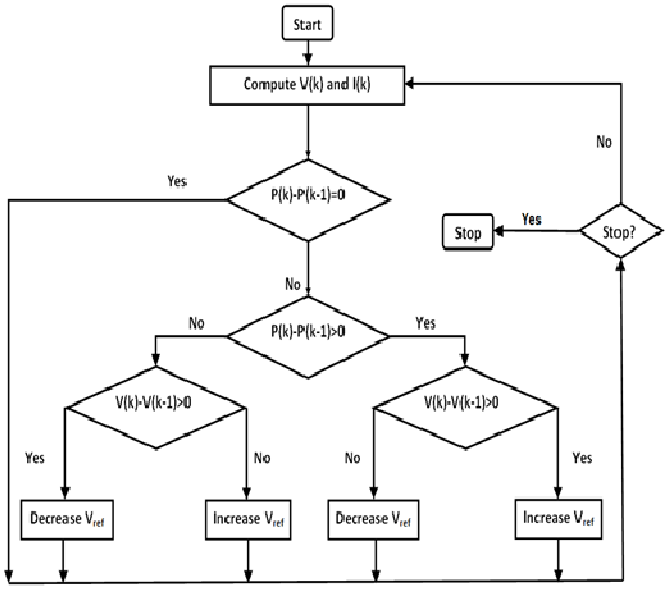

Figure 8. Flowchart of P & O method [26]

4. MATHMATICAL MODEL

From Figure 5, a mathematical model describing the boost converter connected PV generator can be written as:

$$\begin{pmatrix} v_m \\ i_{dc} \end{pmatrix} = m \begin{pmatrix} V_{dc} \\ i_1 \end{pmatrix} \quad (2)$$

and the dynamics of the PV system are

$$\dot{i}_1 = \frac{1}{L_{pv}}(V_m - V_{pv}) - \frac{R_{pv}}{L_{pv}} i_1 \quad (3)$$

$$\dot{V}_{pv} = \frac{1}{C_{pv}}(i_1 - i_{pv}) \quad (4)$$

while the charger's dynamic equation is:

$$\dot{V}_{dc} = \frac{1}{C_{dc}}(i_{dc} - I) \quad (5)$$

where

C_{dc} is the capacitance of the charger's capacitor;

i_{dc} the output current of the regulator;
I the input current of the battery; and
m the boost converter command.

For the last part of the model the equations for the third order battery dynamic model considering the current, electrolyte temperature and SOC, are [16], [17]:

$$\dot{I} = \frac{1}{T_1}\left(\frac{1}{Z_R}[V_{dc}(1-R_0) - E_m + +\frac{V_{dc}R_0A_1Q_e}{K_cCI^{å}} + \frac{K_e(273+\theta)Q_e}{K_cCI^{å}}] - I\right) \quad (6)$$

$$\dot{Q}_e = -[V_{dc}(1-R_0) - E_m + \frac{V_{dc}R_0A_1Q_e}{K_cCI^{\Sigma}} + + \frac{K_e(273+\theta)Q_e}{K_cCI^{\Sigma}}] \quad (7)$$

$$\dot{\theta} = -\frac{1}{C_\theta}[P_s - \frac{\theta - Q_a}{R_\theta}] \quad (8)$$

where,

C_θ is the battery's thermal capacity;
R_0 the thermal resistance between the battery and its environment;
P_S the source's thermal power, i.e., the heat generated internally in the battery;
Q_a the ambient temperature i.e., the temperature of the environment surrounding of the battery;
K_c the empirical coefficient for a given battery; and
I^{Σ} the reference current.

The equations for E_{m0}, R_0, R_1 and R_2 are:

$$E_m = E_{m0} - K_e(273+\theta)(1-SOC) \quad (9)$$

$$R_0 = R_{00}[1 + A_0(1-SOC)] \quad (10)$$

$$R_1 = -R_{10}ln(DOC) \quad (11)$$

$$R_2 = R_{20}\frac{exp[A_{21}(1-SOC)]}{1+exp(A_{22}I_m/I^*)} \quad (12)$$

E_{m0}, K_e, R_{00} and A_1 are constant for a particular battery and the SOC and depth of charge (DOC) can be expressed as:

State of charge $SOC = 1 - Q_e/K_cCI^*$

Depth of charge $DOC = 1 - Q_C/\Theta$

5. LINEARIZATION AND SMALL SIGNAL ANALYSIS OF THE SYSTEM

The linearized form of equations (3)-(8) at maximum power operating point can be written as:

$$\Delta\dot{i}_1 = \frac{m}{L_{pv}}\Delta V_{dc} - \frac{1}{L_{pv}}\Delta V_{pv} - \frac{R_{pv}}{L_{pv}}\Delta i_1 \quad (13)$$

$$\Delta\dot{V}_{pv} = \frac{1}{C_{pv}}\Delta i_1 \quad (14)$$

$$\Delta\dot{V}_{dc} = \frac{m}{C_{dc}}\Delta i_1 - \frac{1}{C_{dc}}\Delta I \quad (15)$$

$$\Delta\dot{I} = \frac{1}{T_1Z_R}[(1-R_0+\frac{R_0A_1Q_e}{K_cCI^*})\Delta V_{dc} + +(\frac{R_0A_1V_{dc}}{K_cCI^*} + \frac{K_e(273+\theta)}{K_cCI^*})\Delta Q_e$$

$$-\Delta IZ_R + (\frac{K_e\theta_e}{K_cCI^*})\Delta\theta] \qquad (16)$$

$$\Delta\dot{Q}_e = -(1 - R_0 + \frac{R_0A_1Q_e}{K_cCI^*})\Delta V_{dc} + +[\frac{R_0A_1V_{dc}}{K_cCI^*} + \frac{K_e(273+\theta)}{K_cCI^*}]\Delta Q_e$$

$$+(\frac{K_e\theta_e}{K_cCI^*})\Delta\theta \qquad (17)$$

$$\Delta\dot{\theta} = \frac{1}{C_0}(1 - \frac{1}{R_0})\Delta\theta \qquad (18)$$

Finally the following equation is used to represent the state space equation of the linearized model of the system:

$$\Delta\dot{x} = A\Delta x \qquad (19)$$

where **A** is the state matrix and x the states of the system.

MPP from the MPPT can be determined as the operating point of the system and then with which the A matrix of the system can be calculated using power system parameters.

Table 1. Eigenvalues with PHEV load

$-2.0162+24.0642\,i$
$-2.0162-24.0642\,i$
-1.1764
$-0.4741+10.0083\,i$
$-0.4741-10.0083\,i$
-2.5300

Table 2. Eigenvalues with constant load

$-0.3026+6.8567i$
$-0.3026-6.8567i$

To predicting the system's responses we conduct a small-signal stability analysis and after linearization of the system the eigenvalues found for the PHEV and constant loads of the same PV system are shown in Table1 and 2, respectively.

From the modal analysis, both the complex and real eigenvalues are found for the PHEVs load. Complex eigenvalues indicates that the system is oscillatory. The more accurate nonlinear simulation results validate those obtained from the small signal analysis. In the case of a constant load of 12 kW which is equivalent to the PHEVs load, the system still has low frequency oscillation which is less in frequency oscillation as well as in magnitude of voltage and current compare to the PHEVs load.

6. SIMULATION RESULTS

To simulate the performance of the stand alone PV system with dynamic PHEV load, a PV array with 15 strings characterized by a rated current of 2 A is used. Each string is subdivided into 15 modules characterized by a rated voltage of 8 V and connected in series. Thus, the total output voltage of the PV array is 120 V, and the output current is 30 A. The value of dc-link capacitor is 250 μF. The line resistance is 0.1Ω and the inductance is 2 *m*H. At this stage, the system is simulated under standard atmospheric condition where the value of solar irradiation is considered as 1 kWm^{-2} and the temperature as 298 K. With this condition, PHEV load has been added to the PV cell and the output voltage of the PV unit is shown in Figure 9 and current in Figure 10 from which it is seen that there are some fluctuation due to the nonlinear characteristics of PV system and dynamic behavior of PHEV. To make a comparison between the constant load and the dynamic PHEVs load effects on PV cell, simulation has been performed under constant radiation and temperature where the simulation result also established the result found from eigenvalue analysis, in Figure 11 and Figure 12.

Due to changes in atmospheric conditions, the output voltage, current, and power of the PV unit change significantly. For example, if a single module of a series string is partially shaded, then its output current will be reduced which will dictate the operating point of the whole string. Therefore variable radiation and temperature have been used to compare the PV cell performance with PHEV loads and constant loads with step variation in radiation from 1000 $W/m^2/h$ to 1300 $W/m^2/h$ at time t=2.5 sec and again back in to the previous condition at t=3.5 sec, which shows that PHEVs load effect the PV performance in voltage and current magnitude as well as in frequency oscillation, as shown in Figure 13, 14,15 and at Figure 16.

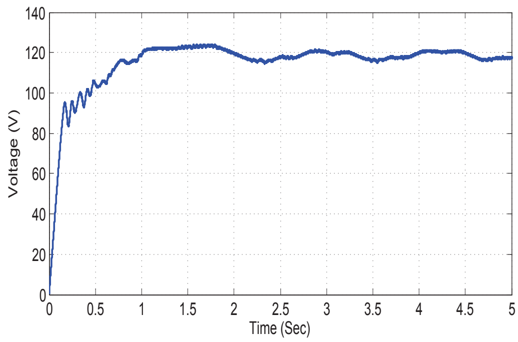

Figure 9. PV cell performance with PHEVs load under constant radiation and temperature (y-axis PV array voltage (V) and x-axis time)

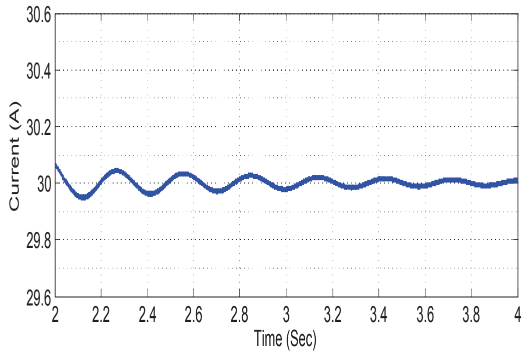

Figure 10. PV cell performance with PHEVs load under constant radiation and temperature (y-axis PV array current (A) and x-axis time)

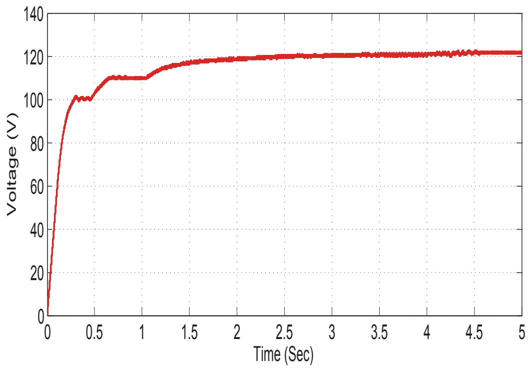

Figure 11. PV cell performance with constant load under constant radiation and temperature (y-axis PV array voltage (V) and x-axis time)

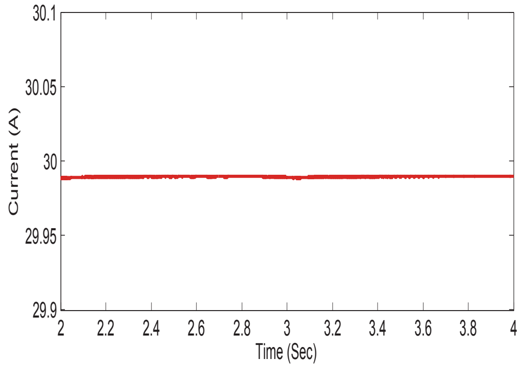

Figure 12. PV cell performance with constant load under constant radiation and temperature (y-axis PV array current (A) and x-axis time)

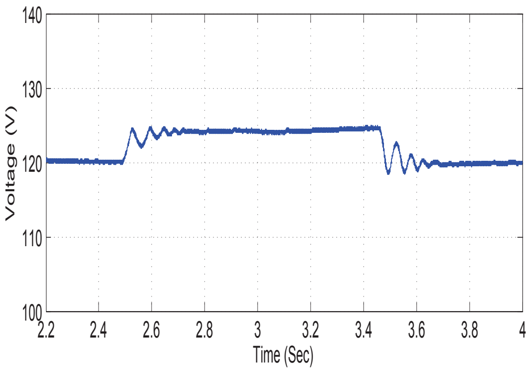

Figure 13. PV cell performance with PHEVs load under variable radiation and temperature (y-axis PV array voltage (V) and x-axis time)

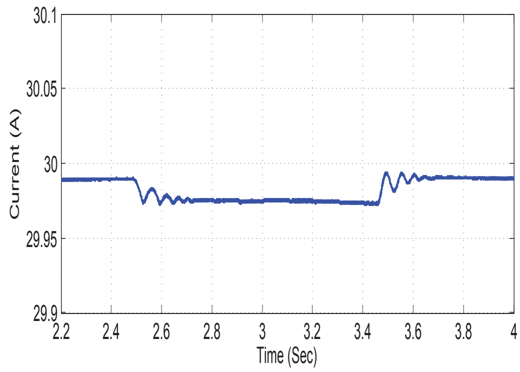

Figure 14. PV cell performance with PHEVs load under variable radiation and temperature (y-axis PV array current (A) and x-axis time)

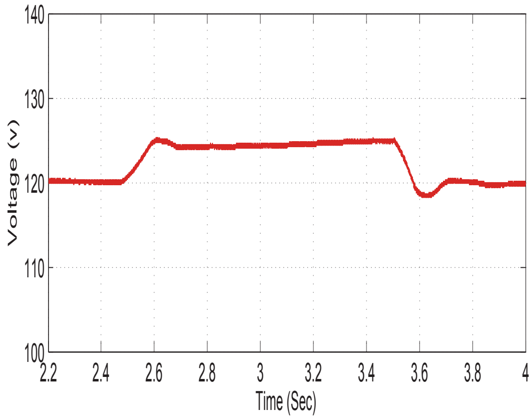

Figure 15. PV cell performance with constant load under variable radiation and temperature(y-axis PV array voltage (V) and x-axis time)

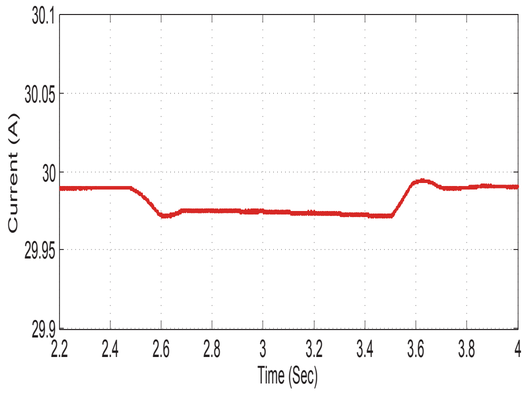

Figure 16. PV cell performance with constant load under variable radiation and temperature(y-axis PV array current (A) and x-axis time)

7. CONCLUSION

The goal achieved via this study is an investigation of the performance of a PV cell with dynamic PHEV loads under constant and variable radiations and temperatures. The obtained results, derived from solving linear circuit equations to calculate the Solar-PHEV eigenvalues, show that while the system without PHEVs is reasonably damped, the introduction of charging PHEVs remarkably increases the amplitude and duration in the voltage and current oscillations, both signs of increased grid instability. The design of future PHEV charging management algorithms will need to consider this effect so as to stabilize the solar system, by introducing damping components when controlling the charging of the PHEV.

It is concluded that a great deal of research into the charging of dynamic PHEV loads through PV cells is needed. Several issues, such as the use of more accurate dynamics of the MPPT, interconnections between the grid and battery and the consequences of ageing for charging with PV cells could be interesting topics for future work.

APPENDIX A

The parameters used for the Battery are as follows:
Parameters referring to the battery capacity:

$$I^{\Sigma} = 49\,A,\; K_C = 1.18, C_1 = 261.9\,Ah$$

Parameters referring to the main branch of the electric equivalent:

$$T_1 = 28800\,s,\; E_{m0} = 2.135V,\; K_e = 0.580e^{-3}V/{}^0C,\; A_0 = -0.30$$

Parameters referring to the parasitic reaction branch of the electric equivalent:

$$E_p = 1.95\,V,\; V_{po} = 0.1V,\; A_p = 2.0$$

Parameters referring to the battery thermal model :

$$C_\theta = 15\,Wh/{}^0C,\; R_\theta = 0.2^0\; C/W$$

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