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Out of Maximum Power Point of a PV system Because of Subharmonic Oscillations

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Abstract—**In this paper, the nonlinear dynamical behavior and stability analysis of a high-voltage-gain quadratic boost converter fed by a photovoltaic (PV) source is addressed. Using the nonlinear models of the converter, the PV source and the MPPT controller, the dynamics of the system are explored in terms of the irradiance using the circuit-level switched model implemented in PSIM© software. The time domain simulations show that at relatively high irradiance levels, the system may exhibit undesired subharmonic oscillations and the Maximum Power Point Tracking control fails to make the system working at the desired maximum power point.**

I. Introduction

Clean renewable energy resources have been given increasing interest in recent years due to concerns about global warming, air quality and sustainable development. It is forseen that in the future power grid the users can produce electric energy by aggregating distributed generation sources such as solar photovoltaic (PV) arrays, wind turbines and batteries forming nano and micro grids. In particular solar photovoltaic (PV) technology is one of the most mature renewable energy technologies and is considered as one of the most environmentally-friendly energy sources since it can generate electricity with almost zero emissions while requiring very low maintenance efforts. Therefore, PV panels are the most important renewable energy sources that can meet power requirements of residential applications. This explains the increasing demand of PV arrays installation hoes and small companies in both grid-connected and in stand-alone operation modes. PV systems use solar arrays to convert sunlight into electrical energy. The voltage and power of a PV source vary according to the climatic conditions, namely temperature and irradiance and therefore a power electronic DC-DC converter is needed for continuously utilizing the maximum available power from the PV source. The maximum power point (MPP) voltage of a PV generator ranges from 15 V to 40 V. Hence, a major challenge that needs to be addressed by the DC-DC converter is to take the low voltage at the output of the solar PV source which varies with solar irradiance and temperature and convert it into a much higher voltage level such as the case of the standard 380DC bus voltage hence requiring a high-voltage-gain DC-DC converter as a power interface. Although, ideally, a simple boost converter operated by a high value of duty cycle can be used in this kind applications, there are many inconveniences with its use mainly related to the system efficiency and the ability of reaching high values of voltage gains in the presence of losses. To overcome this problem, typically, several PV panels are connected in series forming a string to provide a high-voltage at the input of the DC-DC converter hence not requiring of an extremely high value of the duty cycle.

Often, conventional applications of switching converters fed by ideal linear constant voltage sources and loaded by a resistive load are considered. In PV applications, the converter is fed by a nonlinear source and it is usually loaded by *approximately* a constant voltage load. Instabilities in a boost converter for PV applications has been considered in [3], [4]. In [3], the dynamics and stability of a boost converter that is fed from a PV panel and loaded by a resistive load is investigated. In [4], a current mode controlled boost DC-DC converter charging a battery from a PV panel has been considered and its dynamics has been analyzed using the switched model of the converter and the nonlinear model of the PV generator. It has been shown both by theoretical results and experimentally that the nonlinear PV generator combined with the battery's output voltage variation can increase or decrease the converter's stability range. A conflict between stability and efficiency was also reported. In [5] a study of a DC-DC boost converter fed by a PV generator and supplying a constant voltage load is presented. The boundary between the desired periodic behavior and subharmonic oscillation resulting from period-doubling in the parameter space was obtained by calculating the eigenvalues of the monodromy matrix and the results have been validated with time-domain numerical simulation using the circuit-level switched model and also experimentally from a laboratory prototype. Quadratic boost converter for PV systems has also been studied recently from a bifurcation behavior perspective. For instance, in [6] subharmonic oscillations and chaotic behavior have been studied using numerical simulations when the system works in the discontinuous conduction mode (DCM) and the stability regions in term of circuit parameters have been estimated by numerical simulations and confirmed by experimental measurements. In [7], slow scale Hopf bifurcation has been studied in the system with a variable frequency hysteretic current mode control using an averaged model. In [8], the dynamic behavior and stability analysis of a quadratic boost converter supplied by a constant voltage and feeding a resistive load has been addressed.

From the previous literature review, it can be concluded that although some works on stability analysis and bifurcation behavior in quadratic boost converters exist, the analytical determination of its stability boundaries in the multi-dimensional has not been yet addressed to the best knowledge

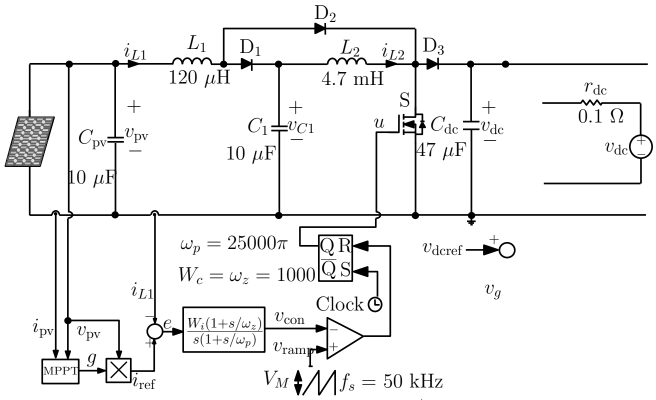

Fig. 1. Quadratic boost converter fed by a PV generator and loaded by a grid-connected micro-inverter.

of the authors. Moreover, the converter has not tackled in the context of PV solar energy systems. In particular, all the previous results reported for this converter consider a constant input voltage and a resistive load while this paper consider a nonlinear PV source voltage and a regulated output voltage load emulating a battery or a DC bus. Hence, in this paper the instabilities of the quadratic boost converter under a fixed frequency PWM control for PV applications is studied with the aim to determine its stability limits in terms of practical parameters such as irradiance and temperature. Complete modeling of the system is addressed mathematically and using PSIM© software. Analysis is carried out by varying the system parameters while maintaining the operation of the system at the MPP, and other parameters of different nature such as those related to climatic changes (irradiance and temperature) and those corresponding to the controller and the modulator. The theoretical results presented in this study are in a very close agreement with the numerical simulations and the experimental measurements. The analysis and the results presented here can also be applied in battery charging applications such as in [9] or a PV-supplied DC motors that can be modeled by its electromechanical force voltage in series with its equivalent resistance [10]. It can also represent a DC link voltage regulated by a grid-connected inverter [11], [12].

The rest of this paper is organized as follows: Section II presents a brief system description and its mathematical modeling. Results concerning the stability analysis from Floquet theory and the associated monodromy matrix are presented in Section III where it is shown that system can undergo period doubling bifurcation leading to subharmonic regime when the parameters of the circuits and the climatic conditions change and it will be observed that once the system enters in subharmonic regime the maximum power point operation is lost.Finally, conclusions of this work are summarized in the last section.

II. System description

A. Operation principle

The schematic diagram of a DC-DC quadratic boost converter fed by a PV generator is shown in Fig. 1. In this kind of applications, the input not the output voltage must be controlled. while the output voltage is fixed by appropriate means. As the solar irradiation S or the temperature Θ change during the operation, the voltage/current of the PV array is adjusted to correspond to the maximum available power. The input side of the DC-DC stage is controlled using a special control for the DC-DC quadratic boost converter defining the required conductance to match the maximum power point of the PV module. The mentioned control is known in the literature as Loss-Free-Resistor (LFR) [13]. With this approach, the input port of the converter behaves as a virtual resistance in average hence improving the stability at the slow scale. The current reference i_{ref} is generated from the input voltage v_{pv}, i.e, $i_{\mathrm{ref}} = g v_{\mathrm{pv}}$. The proportionality factor g is a conductance provided by a maximum power point tracking (MPPT) controller to be described later. The error between the inductor current and the generated reference is controlled by A type-II controller in such a way to regulate the average inductor current, which coincides in steady-state with the average current of the PV panel, to be proportional to the voltage of the PV module. The activation of the switch S is carried out as follows: the output v_{con} of the type-II controller is connected to the inverting pin of the comparator whereas a sawtooth signal v_{ramp} is applied to the non inverting pin. The output of the comparator is applied to the reset input of a set-reset (SR) latch and and a periodic clock signal is connected to the set input of the latch as shown in Fig. 1 in such a way that in steady state the switch S is ON at the beginning of each switching cycle and is turned OFF whenever $v_{\mathrm{con}} = v_{\mathrm{ramp}}$. The state of the diodes D_1 and D_3 are complementary to the switch S while that of D_2 is the same as that of S.

B. The MPPT controller

The PV module has a single operating point where the values of the current i_{pv} and the voltage v_{pv} of the PV module result in a maximum power. These values correspond to a particular load resistance [14]. Its corresponding inductance g_{mpp} is equal to $i_{\mathrm{MPP}}/v_{\mathrm{MPP}}$. Indeed, the power delivered from the PV generator is maximum where its derivative with respect to the PV voltage is zero ($\mathrm{d}P_{\mathrm{pv}}/\mathrm{d}v_{\mathrm{pv}} = 0$) or equivalently where the derivative $\mathrm{d}i_{\mathrm{pv}}/\mathrm{d}v_{\mathrm{pv}}$ is equal in absolute value and opposite in sign to the $i_{\mathrm{pv}}/v_{\mathrm{pv}}$ ratio. A load with conductance $g = i_{\mathrm{pv}}/v_{\mathrm{pv}}$ equal to this value draws the maximum power from the panel. If the conductance g is lower or higher than this value, the power delivered by the PV module will be less than the maximum available as illustrated in Fig. 2. In that figure, operating points A, B and MPP correspond respectively to conductances g_a, g_b and g_{mpp} with $g_b < g_{\mathrm{mpp}} < g_a$. Hence, the PV module can operate at the MPP by appropriately selecting the value of the conductance that leads to an intersection of the PV $i-v$ characteristic curve and the conductance load line at the MPP. This conductance is a dynamic quantity which changes depending on the level of irradiance and other parameters such as temperature and aging and hence an automatic tracking of its value is needed. MPPT is a technique commonly used in PV solar systems to optimize power extraction regardless the weather conditions

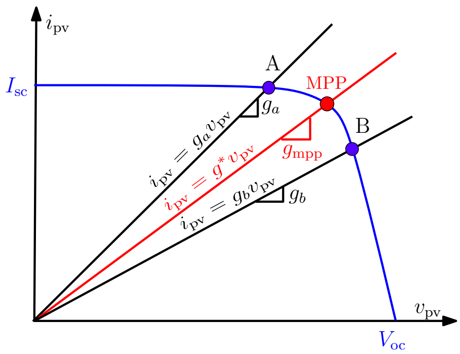

Fig. 2. PV module operating points for an impedance matching between the PV generator and the LFR.

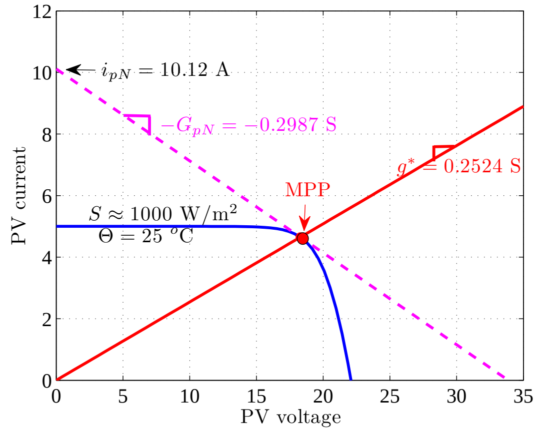

Fig. 3. PV module characteristic (a) $i - v$ characteristic and its linear approximation (dashed) at the MPP for $S = 1000$ W/m^2 and $\Theta = 25\ ^o$C. The load line of the optimum conductance $g_{\rm mpp} = 0.2524$ S, is also shown.

[15]. Among all the existing methods, perturb and observe (P&O) is the most commonly used MPPT technique due to its ease of implementation and high efficiency. In conventional (P&O) techniques, the controller changes the PV voltage by small increments and subsequently measures the resulting power in such a way that if the power increases, further change in the same direction is performed until the measured power no longer increases. In this paper the change is performed directly on the conductance g.

C. The PV generator

A photovoltaic module, for a large part of its useful curve, acts as a constant current source and this can be used as a model for the nonlinear PV generator as in [5]. However, close to the MPP, the descriptive equation of the PV generator can better be linearized by expanding its nonlinear model as a Taylor series and ignoring high order terms. This would reveal better the effect of the parameters that arise due to the nonlinear nature of the generator. In [16] it was demonstrated that the following linear equivalent model can be used for the PV panel close to the MPP:

$$i_{\rm pv} \approx i_{\rm mpp} - G_{pN}(v_{\rm pv} - v_{\rm mpp}). \quad (1)$$

Hence, the equivalent Norton current i_{pN} is given by:

$$i_{pN}|_{v_{\rm pv}=v_{\rm mpp}} = i_{\rm mpp} + G_{pN} v_{\rm mpp}, \quad (2)$$

where G_{pN} is the equivalent conductance close to the MPP which can be expressed as follows:

$$G_{pN} = \frac{v_{\rm ta} + R_p I_o e^{\frac{v_{\rm mpp}+R_s i_{\rm mpp}}{V_{\rm ta}}}}{R_s R_p I_o e^{\frac{v_{\rm mpp}+R_s i_{\rm mpp}}{V_{\rm ta}}} + (R_s + R_p)V_{\rm ta}}. \quad (3)$$

where $v_{\rm pv}$ is the voltage of the module, $I_{\rm pv}$ and I_s are the photogenerated and saturation currents respectively, $V_{\rm ta}$ is the thermal voltage which is given by $V_{\rm ta} = N_s AK\theta/q$ where A is the diode quality factor, K is Boltzmann constant, q is the charge of the electron, Θ is the PV module temperature and N_s is the number of the cells connected in series. The photogenerated current $I_{\rm pv}$ depends on the irradiance S and temperature Θ according to the following equation:

$$I_{\rm pv} \quad = \quad I_{\rm sc}\frac{S}{S_n} + C_\Theta(\Theta - \Theta_n), \quad (4)$$

TABLE I
PARAMETERS OF THE PV MODULE.

Parameter	Value
Number of cells N_s	36
Standard light intensity S_n	1000 W/m^2
Ref temperature Θ_n	25 ^{o}C
Series resistance R_s	0.005 Ω
Parallel resistance R_p	1000 Ω
Short circuit current I_{sc}	5 A
Saturation current I_0	1.16·10^{-8} A
Band energy E_g	1.12
Ideality factor A	1.2
Temperature coefficient C_Θ	0.00325 A/^{o}C

where $I_{\rm sc}$ is the short circuit current, Θ_n and S_n are the nominal temperature and irradiance respectively and C_Θ is the temperature coefficient. Practical PV generators have a series resistance R_s and a parallel resistance R_p which can be ignored for simplicity purposes. The PV module considered in this study has a nominal power of 85 W [17] and its parameter values are depicted in Table I. Fig. II-C shows the PV module $i - v$ curve together with its linearized approximation close to the MPP for $S = 1000$ W/m^2 and $\Theta = 25\ ^o$C. The load line of the optimum value of the conductance $g_{\rm mpp} = 0.2542$ S is also shown in the same figure.

III. THE SOLAR PV SYSTEM BEHAVIOR AND STABILITY ANALYSIS OF PERIODIC ORBITS

Before giving a detailed study of the behavior of the system and its stability boundaries, let us take a quick glimpse at some of its typical operating regimes when some suitable factors such the weather conditions change. The simulations are performed using PSIM© software where the PV panel model can be implemented using the physical model of the solar cell in the renewable energy package.Let us use the set of parameter values shown in Fig. 1 for the quadratic boost converter and those in Table I for the PV module. The

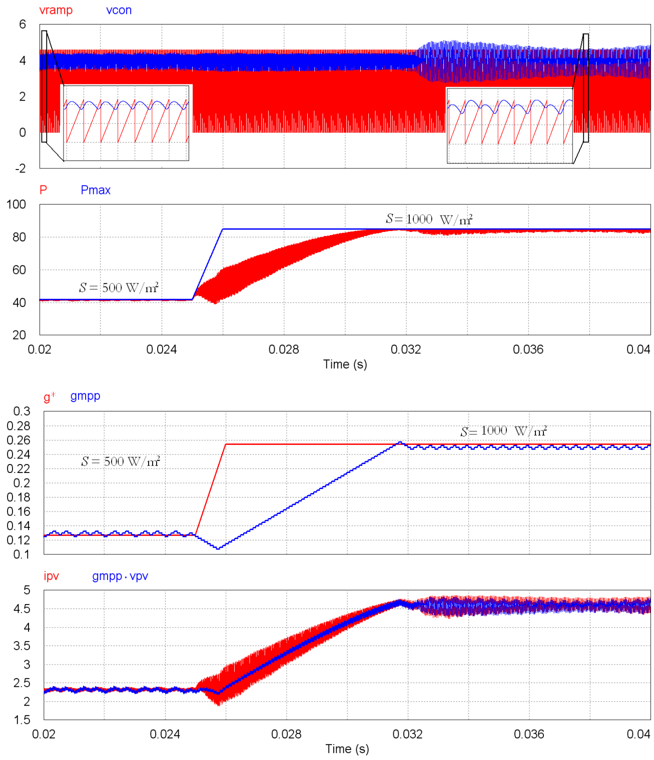

Fig. 4. The waveforms of the system under a change in the irradiance level.

time domain waveforms shown in Fig. 4 the exact circuit-level model implemented in PSIM© software by taking into account the P&O MPPT controller performed by the dynamic conductance g and considering the DC bus regulated to 380 V superimposed to 5 V peak-to-peak ripple. The only acceptable operating regime employed in practical power supplies for different applications is the fundamental periodic regime characterized with a regular repetition of the waveforms each switching period T.

Fig. 4 shows the waveforms of the control signals, the power and the dynamic inductance g of the system under a change in the irradiance level. A zoomed view of the ramp modulator signal and the control voltage is also shown. In this zoomed view, one can note that a fundamental periodic operation (stable) takes place for low irradiance levels while it is possible that when the irradiance increases, other operating regimes are possible. For example, when the irradiance increases to $S = 1000$ S/m^2, subharmonic operation is exhibited. It can observed also from Fig. 1 that whenever the subharmonic instability takes place, the MPPT controller is disappointed since the value of the conductance g_{mpp} provided by this controller deviates from the theoretical one $g^* = i_{\text{mpp}}/v_{\text{mpp}}$ which could result in serious problems related to efficiency degradation.

Conclusions

The dynamics of a high-voltage-gain quadratic boost converter fed with a PV generator for high-voltage-gain solar energy applications has been studied in this paper. The system can exhibit period doubling under climatic conditions, loading and control parameter changes. It is also shown that the subharmonic oscillations and other complex dynamics can make the MPPT controller to a work out of the maximum power point.

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