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Research Article

A Robust H_∞ State Feedback Controller For Mppt Control Based On The Mean Value Theorem

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***Abstract* –** This paper presents a new strategy for a maximum power point (MPP) tracking MVT controller for photovoltaic (PV) systems subject to atmospheric condition variations. A DC-DC boost converter is used to connect a PV panel with an output load. The output voltage of the DC-DC boost converter can be adjusted by duty ratio that is limited between two values. The objective of our control design is to track the MPP. To minimize and stabilize the tracking error with disturbance effect, the dynamic behaviour of a PV system and its reference model are described by using men value theorem (MVT) and sector linearity's (SNL). Then, a robust H_∞ PI-controller based on state feedback control is proposed. The control approach design is used to establish the stability conditions of the closed-loop system which is formulated and solved using Lyapunov theory that are transformed in terms of linear matrix inequalities LMI s. Finally, simulation results are given to show the tracking performance of the control design.

Key Words: Photovoltaic (PV) System, Maximum Power Point Tracking (MPPT), MVT Model, Linear Matrix Inequalities (LMIS)

1. INTRODUCTION

Photovoltaic (PV) energy has been the subject of several research projects in recent years which is motivated by environmental concerns and the depletion of fossil fuels, so an increased attention has been given to other energy sources like: Fuel cells [1], biomass plants [2],, and photovoltaic arrays [3,4,5] which represent the most practical and interesting renewable energy systems. Photovoltaic systems have the advantage of converting Solar light energy into electrical energy by the photovoltaic phenomena. The collected power can be stored in a battery, used instantly or can be transformed to other forms like a centralized grid [12] connections . It is well known that the PV array power panel depends on two pair ,climatic variables such as temperature and irradiation.

As we know that the operating point of the PV array panel depends on three parameters such as temperature, irradiation, and the load. In fact, the operating point results from the intersection of the I-V characteristic and the load characteristic . In most cases, the value of load is constant and the climatic parameters vary in the day, so the load characteristic remains fixed and the characteristic of the panel varies according to climatic variables. Consequently, the operating point is variable and the load cannot extract maximum power from the panel [6,7,8]. So, the power solar panels have nonlinear power–voltage-current (P–V-I) characteristics. The output power depends on temperature, solar radiation and output voltage. Thus, many algorithms and controllers have been proposed in the literature to maximize PV power transfer to various loads.

The most important conventional algorithms are perturb and observe (P&O) , incremental conductance (InCond) and hill climbing (HC) [2,3 and 5]. These algorithms are widely used in commercial PV panels due to their simplicity, low cost and easy implementation, but on the other hand they suffer from serious drawbacks such as slow tracking of MPPT during a rapid change of atmospheric conditions and considerable oscillation around the MPPT [15,16].A comparative study of P&O, In Cond and HC carried out in [10,15] concluded that these methods are actually equivalent and deliver similar performance. In order to overcome some of these drawbacks ,many algorithms and control strategies have been proposed that are unable and suffering to find the true MPP due to the approximation used in these methods.

In order to overcome these drawbacks and remedy the disadvantages of the previous methods which have been quoted above, an MVT approach can avoid a such constraints.The MVT approach for the control was recently used in [11,14] for the control and observation of the states where the authors transfer the nonlinear model to the Lipschitz form and then use the MVT and sector nonlinearity to find the control gains by solving the LMI’s inequalities. In this paper, the PI state feedback control problem is used to control the PV solar energy which is studied using these approaches. First, the nonlinear system is transferred to the Lipschitz form, then the nonlinear control error state dynamics of the suggested MVT controller [11] is designed and expressed as a convex combination of known matrices with time varying coefficients as a LPV systems. Using the Lyapunov theory [11,15,16], so, stability conditions are obtained and expressed in terms of linear matrix inequalities, and the controller gains are obtained by solving the LMIs using Yalmip tools. The main advantage of the MVT approach in this work is to find the controller gains which is calculated off line with a proven methodology that stabilize the control error state of the solar panel system energy even in presence of a disturbance and doesn’t depend on the states of the PV solar contrarily as in TS fuzzy models that using the PDC fuzzy controller [14,15,16] need for each rule attributed a weight which depends on grade of membership function of premise variables in fuzzy set should be calculated .

This paper is arranged as followings: modelling of the PV solar panel system and the MVT state feedback control strategy is performed in Section 2 using MVT and SNL which is divided into regular nonlinear model in the first subsection and in the Lipschitz model in subsection 2.2, whereas the generator reference states is developed in the last subsection. Section 3 provides the design of the controller based on the MVT approach and sector nonlinearity. In Section 4, simulation results and its discussion were performed to prove the effectiveness of suggested concept. Conclusions and perspectives are noted in Section 5.

2. Modelling and references generator of the PV system

2.1 Nonlinear model of the PV solar panel system

The photovoltaic PV solar panel system power depends on climatic parameters such as temperature and irradiation [9,10]. In fact, the photovoltaic power, which is transmitted to the load, is function of the impedance of the load and the climatic parameters as shown in Figure 2.However, to change the impedance seen by the panel, it is necessary to insert a DC/DC converter. The photovoltaic system consists of a photovoltaic array panel connected to a DC-DC converter which provides energy to the load, as shown in Figure 1. In conclusion, we can say that the PV array panel is nonlinear and time-variant system. It is clear that the temperature affects essentially the voltage and the irradiation affects fundamentally the intensity of the PV array panel. Also, we can conclude that the output power generated by the PV array panel depends on the climatic parameters "G and T." In fact, the power increases with an increase in solar radiation and decreases with an increase in temperature. For each given pair of parameters (G,T),there exists only one Maximum Power Point (MPP).

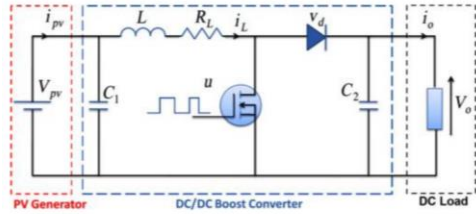

Fig. 1 Photovoltaic system

The operating point is determined by the intersection of the panel current-voltage characteristic and the load current-voltage characteristic. So, the PV cell model is described by the following equations[9,10]:

$$i_{PV} = n_p I_{ph} - n_p I_s \left(exp\left[\frac{q(V_{PV} + R_s i_{PV})}{kTA}\right] - 1 \right) - \frac{V_{PV} + R_s i_{PV}}{R_{sh}} \tag{1}$$

Such that:

$$I_{ph} = G\left(I_{sc} + K_I(T - T_r)\right) \tag{2}$$

And

$$I_s = I_{rs}\left(\frac{T}{T_r}\right)^3 exp\left[\frac{qE_g}{kA}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \tag{3}$$

Where $I_{rs}$is a reverse saturation current such that :

$$I_{rs} = \frac{I_{sc}}{exp\left[\frac{qV_{oc}}{n_s kAT}\right] - 1} \tag{4}$$

$$V_{oc} = n_s \frac{KT}{q} log\left(\frac{I_{sc} + I_0}{I_0}\right) \tag{5}$$

with V_{oc} is the open circuit voltage and I_{sc} is the short circuit current.

It is very clear that the system composed of PV-Boost-Converter-Load can be represented after adding a new state variable in order that the overall system can possess an integration state as follows:

$$\begin{cases}\dot{x}(t) = f(x(t)) + Bu(t) + D_w w(t) \\ y = Cx(t)\end{cases} \quad (6)$$

Where

$$f(x(t)) = \begin{bmatrix} \frac{-R_L+R_D}{L} & \frac{1}{L} & \frac{-1+x_4}{L} & \frac{-R_D x_1+v_D}{L} \\ -\frac{1}{C_1} & 0 & 0 & 0 \\ \frac{1}{C_2} & 0 & -\frac{1}{C_2 R_L} & -\frac{x_1}{C_2} \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad ; \quad D_w = \begin{bmatrix} -\frac{1}{L} & 0 \\ 0 & \frac{1}{C_1} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \; and \; w(t) = \begin{bmatrix} v_D \\ i_{PV} \end{bmatrix} \quad (7)$$

2.2. References generator for optimal conditions

To assure the condition for the optimal reference model variables x_{op}(t) which can be obtained using previous equations and can be rewritten as follows[16] :

$$i_{Lop}(V_{PVop}) = i_{PV} - C_1 \dot{V}_{PVop} \quad (8)$$

And

$$\mu_{PVop}(V_{PVop}) = \frac{1}{\alpha}\left(\frac{R_L}{L} i_{Lop} - \frac{1}{L} V_{PVop} + \beta + \dot{i_{Lop}}\right) \quad (9)$$

3. Problem Statement

An efficient methodology will be presented in this subsection for designing controllers for the class of the PV model system energy which described as (7). We can represent the PV system energy as the Lipchitz form [12]:

$$\begin{cases}\dot{x}(t) = A_0 x(t) + B_0 u(t) + \Phi(x(t)) + Dw \\ y = Cx(t)\end{cases} \quad (10)$$

Where

$$\Phi(x(t)) = f(x(t)) - A_0 x(t) \quad (11)$$

The state vector of the error is written as:

$$e(t) = x(t) - x_c(t) \quad (12)$$

Where x_c is the reference state and it is supposed as stepwise signal, the dynamics of the state error as the following:

$$\dot{e}(t) = \dot{x}(t) - \dot{x}_c(t) = \dot{x}(t) = A_0 x(t) + B_0 u(t) + \emptyset(x) + Dw(t) \quad (13)$$

3.2 Augmented state feedback control

To eliminate the effects of disturbance and the parametric uncertainty in the steady state, it is better to add an integral action, so the control is rewritten as:

$$u(t) = -[K_1 \quad K_2]\begin{bmatrix} e(t) \\ e_I(t) \end{bmatrix} = K_I \bar{e}(t) \quad (14)$$

Such as the error state bound the integral action is:

$$\dot{e}_I(t) = x(t) - x_c(t) \quad (15)$$

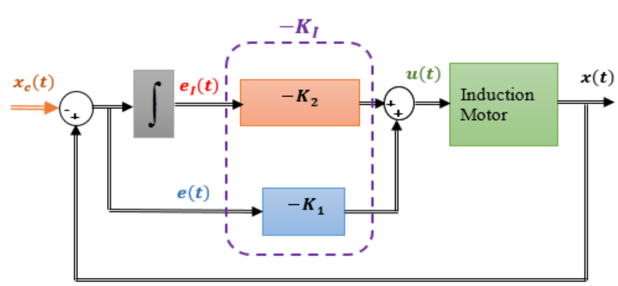

Fig. 2. Augmented MVT control design

By introducing (12) combined with (13) in the state error of the closed-loop control (4), we can obtain that the dynamics of augmented state error can be written as:

$$\dot{\bar{e}}(t) = \sum_{i=1}^{r} \mu_i(\xi)\left(\bar{S}_i \bar{e}(t) + \bar{D}_w \bar{w}(t)\right) \quad (16)$$

Where:

$$\bar{S}_i = \bar{A}_i - \bar{B}K_I$$

And

$$\bar{A}_i = \begin{bmatrix} \mathcal{A}_i & 0 \\ I & 0 \end{bmatrix} \qquad \bar{B} = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

$$\overline{D}_w = \begin{bmatrix} A_0 & D \\ 0 & 0 \end{bmatrix} \qquad \overline{w}(t) = \begin{bmatrix} x_c(t) \\ w(t) \end{bmatrix}$$

3.2.1 Synthesis for H_∞performance

In this section, we illustrate the formulation for H_∞ performance for the PI controller (the same for P controller).

The existence of the disturbances $\overline{w}(t)$ will affect to the control performances. So as to minimize the effect of the disturbance $\overline{w}(t)$, the H_∞ performances related the state feedback control error has been taken into account [9]

$$\int_0^\infty \bar{e}^T(t)\,\bar{e}(t)\,dt \le \gamma^2 \int_0^\infty \overline{w}^T(t)\,\overline{w}(t)\,dt \qquad (17)$$

Consider the quadratic Lyapunov function as:

$$V\big(\bar{e}(t)\big) = \bar{e}^T(t)P\bar{e}(t) \qquad (18)$$

Where $P = P^T > 0$

So as to develop the asymptotic stability of (10) and to attain the H_∞ performance of the state control error, the time derivative of $V\big(\bar{e}(t)\big)$ has the following condition:

$$\dot{V}\big(\bar{e}(t)\big) + \bar{e}^T(t)\bar{e}(t) - \gamma^2\overline{w}^T(t)\overline{w}(t) < 0 \qquad (19)$$

Replacing (18) in (19), the pervious equation becomes as a LMI form as next:

$$\dot{\bar{e}}^T(t)P\bar{e}(t) + \bar{e}^T(t)P\dot{\bar{e}}(t) + \bar{e}^T(t)\bar{e}(t) - \gamma^2\overline{w}^T(t)\overline{w}(t) < 0 \qquad (20)$$

This is equivalent to:

$$[\bar{e}^T(t) \quad \overline{w}^T(t)] \begin{bmatrix} \sum_{i=1}^{r} \mu_i\big(x(t)\big)\left[\bar{S}_i^{\,T}P + P\bar{S}_i + I\right] & P\overline{D}_w \\ \overline{D}_w^{\,T}P & -\gamma^2 I \end{bmatrix} \begin{bmatrix} \bar{e}(\\ \overline{w}(\end{bmatrix} < 0 \qquad (21)$$

(19) is transformed to:

$$\begin{bmatrix} \sum_{i=1}^{r} \mu_i\big(x(t)\big)\left[\bar{S}_i^{\,T}P + P\bar{S}_i\right] & P\overline{D}_w \\ \overline{D}_w^{\,T}P & -\gamma^2 I \end{bmatrix} + \begin{bmatrix} I \\ 0 \end{bmatrix}[I \quad 0] < 0 \qquad (22)$$

Depending on the Schur's complement and by applying the congruence transformation, multiplying to the right and to the left by the $diag\,[P^T, \quad I, \quad I]$,(22) becomes as follow:

If we consider that $X^{-1} = P$ and $Y = K_I P^{-1} = K_I X$, we obtain the final LMI to be solved:

$$\begin{bmatrix} \bar{A}_i X + X\bar{A}_i^{\,T} - \bar{B}Y - Y^T\bar{B}^T + \alpha X & \overline{D}_w \\ \overline{D}_w^{\,T} & -\gamma^2 I \\ X & 0 \end{bmatrix} < 0 \qquad (23)$$

Such as the augmented PI-controller, the gain K_I has been obtained as follows:

$$K_I = [K_1 \quad K_2] = YX^{-1} \qquad (24)$$

For the simple state feedback P control, the LMI's equation (23) becomes:

$$\begin{bmatrix} A_i X + XA_i^{\,T} - BY - Y^T B^T + \alpha X & D_w \\ D_w^{\,T} & -\gamma^2 I \\ X & 0 \end{bmatrix} < 0 \qquad (25)$$

Where the proportional controller gain has been gotten as:

$$K_p = YX^{-1} \tag{26}$$

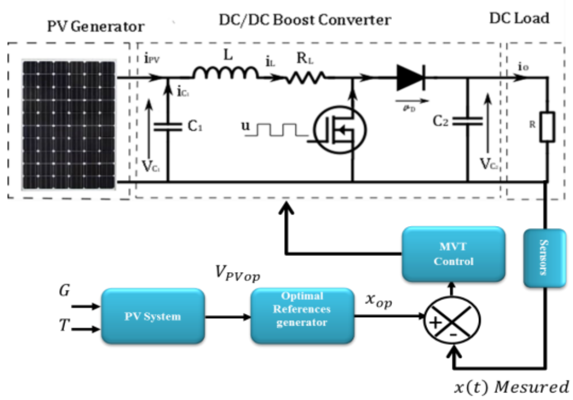

Fig. 3.Robust H_∞ −MVT state feedback control design

Combining (12) with (13), the dynamics of the state error is:

$$\dot{e}(t) = (A_0 - B_0K_0)e(t) + A_0x_c(t) + \Phi\big(x(t)\big) + Dw(t) \tag{27}$$

With :

$i_L = x_1$,$v_{C_1} = x_2$,$v_{C_2} = x_3$, $\mu = x_4$ and $\dot{\mu} = u$

$$\emptyset(x) = \begin{bmatrix} \frac{1}{L}(-R_Dx_1 + x_3)x_4 \\ 0 \\ x_1x_4 \\ 0 \end{bmatrix} \text{ and } A_0 = \begin{bmatrix} \frac{-R_L+R_D}{L} & \frac{1}{L} & -\frac{1}{L} & \frac{v_D}{L} \\ -\frac{1}{C_1} & 0 & 0 & 0 \\ \frac{1}{C_2} & 0 & -\frac{1}{C_2R_L} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

By using the MVT [10, 12,13] , we have:

$$\frac{\partial f}{\partial x}(\varepsilon) = \frac{\partial \Phi\big(x(t)\big)}{\partial x}(\varepsilon)(x - x_c) - A_0 \tag{28}$$

Where $\varepsilon \in [x, x_c]$;so

$$\frac{\partial \Phi\big(x(t)\big)}{\partial x} = \begin{bmatrix} 0 & 0 & 0 & -\frac{R_D}{L} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_2} \\ 0 & 0 & 0 & 0 \end{bmatrix} x_1 + \begin{bmatrix} 0 & 0 & 0 & \frac{1}{L} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} x_3 + \begin{bmatrix} -\frac{R_D}{L} & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{1}{C_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} x_4$$

Next, one can apply sector nonlinearity approach with the following assumptions:

$$\underline{\xi}_{ij} \leq \frac{\partial f_i}{\partial x_j}(\varepsilon) = \xi ij \leq \overline{\xi}_{ij} \;;\; \overline{\xi}_{ij} \geq max(\frac{\partial f_i}{\partial x_j}(\varepsilon)\underline{\xi}_{ij} \leq min(\frac{\partial f_i}{\partial x_j}(\varepsilon))$$

Such that each nonlinearity can be replaced using the sector nonlinearity

$$\sum_{i=1}^{n}\sum_{j=1}^{n} e_n(i)e_n^T(j)\frac{\partial \Phi_i}{\partial x_j} = \sum_{i}^{n}\sum_{j}^{n}(\delta_{ij}^1 Hij.\overline{\xi}_{ij} + \delta_{ij}^2 Hij.\,\underline{\xi}_{ij})$$

Where the weighting functions

$$\begin{cases} \delta_{ij}^{1} = \dfrac{\frac{\partial f_i}{\partial x_j} - \underline{\xi}_{ij}}{\overline{\xi}_{ij} - \underline{\xi}_{ij}} \\ and \qquad\qquad \text{with} \sum_{e=1}^{2} \delta_{ij}^{e} = \\ \delta_{ij}^{2} = \dfrac{\overline{\xi}_{ij} - \frac{\partial f_i}{\partial x_j}}{\overline{\xi}_{ij} - \underline{\xi}_{ij}} \end{cases}$$

$$1 \text{ such that} 0 \leq \delta_{ij}^{e} \leq 1 \quad (29)$$

Hij is a zeros matrix elsewhere unless in the position indicated by the i_{th} raw and j_{th} column it takes one.

By using results in (16) and (17) and with the following notations:

$\mu_1(\xi) = \delta_{11}^{1}$,$\mu_2(\xi) = \delta_{11}^{2}$,$\mu_3(\xi) = \delta_{12}^{1}$,$\mu_4(\xi) = \delta_{12}^{2} \ldots$

$\ldots \mu_{2n}(\xi) = \delta_{1n}^{2} \ldots\ldots\ldots\ldots \mu_r(\xi) = \delta_{2n2n}^{2}$.

And $\mathcal{A}_1 = H11.\overline{\xi}_{11}$,$\mathcal{A}_2 = H11.\underline{\xi}_{11}$,$\mathcal{A}_3 = H12.\overline{\xi}_{12}$,

By choosing the permissible variables

$\xi_1 = x_1$, $\xi_2 = x_3$ *and* $\xi_3 = x_4$ such that: $m_i < \xi_i < M_i$

As long as $0 < x_4 < 1$

Then :

$$\mathcal{A}_1 = \begin{bmatrix} 0 & 0 & 0 & -\frac{R_D}{L} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_2} \\ 0 & 0 & 0 & 0 \end{bmatrix} m_1; .. \ \mathcal{A}_6 = \begin{bmatrix} -\frac{R_D}{L} & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{1}{C_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} M_3$$

4. Simulation results

The suggested controller design is implemented and the simulation results are obtained under Matlab/Simulink environment. To appreciate the effectiveness of this design conception is suggested which has the following parameters . The main characteristics of the PV array panel are given by Table 1.The resolution of the LMIs gives the following augmented feedback gain:

$$K_0 = (32.01 \ \ 12.58 - 8.02 \ \ 152.80 \ \ 10.38 \ - 0.28)$$

Table:1	Characteristics of the PV array panel
n_s	= 1
n_p	=36
q	$= 1.6e - 19C$
A	= 1.92
E_g	= 1.1
T_r	= 298.18°K
T_r	= 25°C
I_{or}	$= 9.579e \ - 6 \ A$
V_{co}	= 27.4 V
R_s	= 0.09 Ω
R_{sh}	= 100 Ω
R_{load} =R_L	= 45 Ω
P_{max}	= 61 W
I_{sc}	= 4.8 A
K_I	= 0.00171 A/°C
f	= 20 Khz
C_1 and C_2	= 10 and 68 μF respectively.
k	$= 1.38e - 23$ J/K(Boltzmann's constant)

To demonstrate the performance of the proposed MPPT control approach, we apply a sudden variation of temperature and solar irradiation as shown in Figure 3 . We know that for each pair there exists only one optimal operating point which can be determined from the power-voltage characteristics of the PV array panel dynamically providing the optimal references .

The dynamic responses of v_{c1} input voltage, v_{c2} output voltage timet, the current inductor i_L and μ the duty cycle of the boost converter were given in the following figures 3,4,5,6 and 7.Theses figures show that the proposed MVT controller presents a better MPPT performance and, especially, a very interesting settling and an output that follows accurately the reference signal with less transient-state oscillations. However, the MVT-P controller exhibits sensitivity to an abrupt irradiation and temperature changes resulting a ripple during the transient period which leads to an inexact MPP voltage tracking.

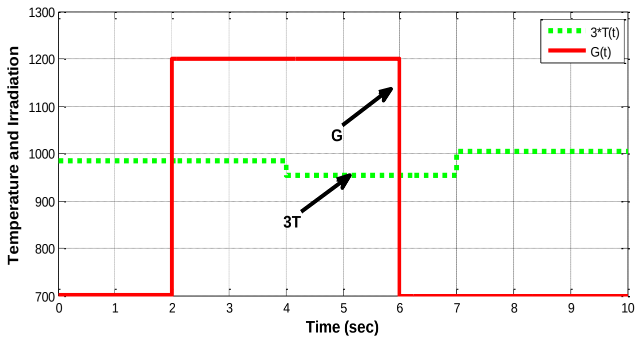

Fig. 3: Evolution of temperature. and irradiation

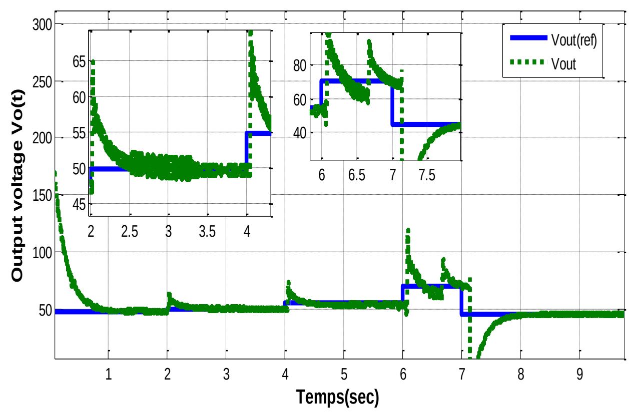

Fig. 4: Output voltage. and its reference

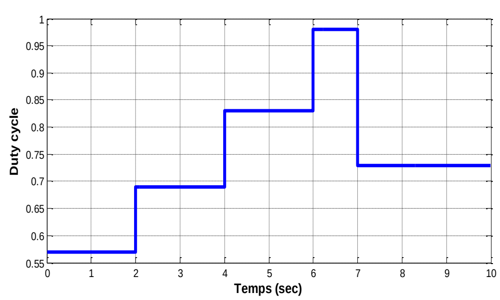

Fig. 5 : Duty cycle of the boost converter

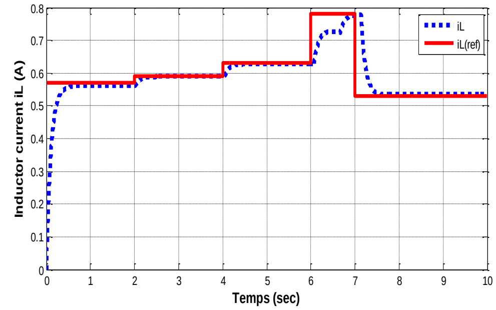

Fig. 6 : Inductor current and its reference

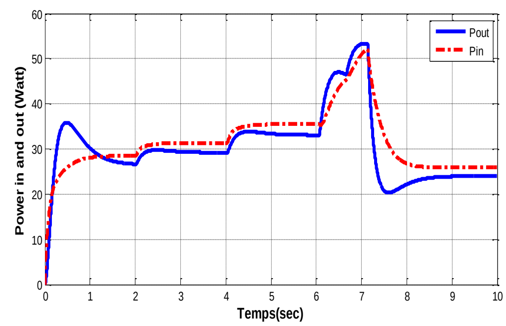

Fig. 7 : Input and ouput power of the PV system.

5. Conclusion

This paper presents a robust MVT-PI- state feedback controller, indirectly, for maximum power point (MPP) tracking of PV systems obtained from the seeker or reference generator. The concept of the MVT controller is designed for the combined -PV-System and DC/DC boost converter with a new algorithm strategy based on the MVT and the sector nonlinearity approach that is performed to track the optimal states generated from the seeker fulfilling the desired output which is the gradient of the power to the voltage should be zero. Based on the new model representation, stabilization conditions of the closed-loop system which is formulated and solved in terms of linear matrix inequalities MLI s. All the works of the PV system that have been modelled by T-S fuzzy systems ,their controllers depend on the states of the PV solar when using the PDC fuzzy controller state feedback that each rule is attributed a weight which depends on grade of membership function of premise variables in fuzzy set. Based on the temperature and irradiation variations, we can deduce that the coordinates of the desired optimal operating point which corresponds to the maximum power. The algorithm implemented is based on a PI-state feedback method based on MVT and SNL . The controller gains have been computed based on the LMI s tools after stabilising the PV-system in closed loop that have been proved using Lyapunov approach. The simulation results show that the proposed algorithm tracks quickly the optimal operating point despite sudden variations of temperature and irradiation with minor errors. The obtained simulation results show that the proposed controller is able to track the MPP with fast convergence even under changing climatic conditions. Future works will focus on experimental validation of these approaches and we take in consideration all the limitations and constraints to reduce the errors and fast responses to perturbations or to the desired references generated by the seeker.

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