Modelling and non linear control of a photovoltaic system with storage batteries: A bond graph approach

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Abstract. *This paper presents a bond graph modelling of a photovoltaic source (PV). The insolation variation during the day poses the problem of energy storage. For that, we used electrochemical batteries which present the best solution by their good adaptation to photovoltaic source. A maximum power point tracking (MPPT) device is located between PV array and batteries to optimise the power transfer from the PV array and batteries. A non linea control approach of a photovoltaic system is introduced for the DC-DC converter. The control strategy is based on state feedback input output linearization, and the control law is determined from the established bond-graph model.*

Key words:
bond graph, photovoltaic source, nonlinear control, storage battery, DC/DC converter.

1. Introduction

In rural zones, conventional sources of energies are limited, and photovoltaic energy (PV) becomes a promising solution. In fact, many advantages are presented by this energy like the availability on a large scale of planet area. A stand alone photovoltaic system generally uses batteries to maintain supply when the solar energy is not available [5]. In order to overcome the undesired effect of the PV output voltage, and to assure its maximum power point operating, it's possible to insert a DC-DC converter (MPPT) between the PV generator and the batteries [3]. There is a thorough study found a MPPT control , In order to guide the generator towards the optimum power point and to exploit the maximum energy delivered by the photovoltaic generator. Where [21] develop a PWM control strategies, [20] use genetic assisted, multi-layer perceptron neural network control,[18]and [19] use fuzzy logic control. In this paper, considering the nonlinear characteristic I-V of the PV system, a non linear (N.L) control law is developed for this system . To exploit the model bond graph of the photovoltaic system, The control law is determined from the established bond-graph model [8][9]. In the first part of this paper, the B.G model for different elements of the system is presented. In the second part, a theoretical study of the nonlinear control is presented, and the non linear approach for the control based on the B.G model for the system and state feedback linearization is developed, Finally, different simulations are presented.

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2. Bond graph modelling for the photovoltaic source

2.1 The PV array model

The PV array is basically formed by solar cells. The equivalent circuit model of a solar cell consists of a current generator (I_{ph}) and a diode (D), serial (R_s) and parallel (R_{sh}) resistances [2]. The equation (1) refers to the PV array current. The equivalent circuit is given by figure.1[2] [10].

$$I_p = I_{ph} - I_s[\exp(\frac{V_p + R_s I_p}{V_T}) - 1] - \frac{V_p + R_s Ip}{R_{sh}} \quad (1)$$

In literature, a model simplification is often done. This simplification consists in neglecting resistances R_s and R_{sh} which facilitates considerably the exploitation of the PV generator model by avoiding the implicit equations. The simplified equation of the photovoltaic courant introduced by [2] is given as follows:

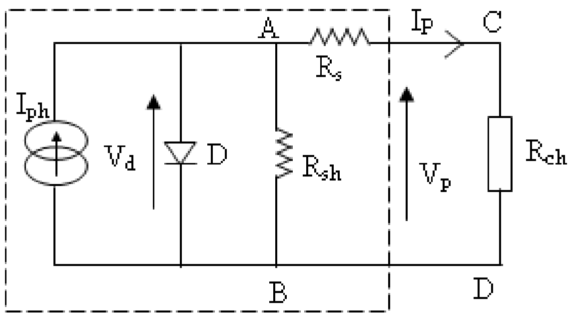


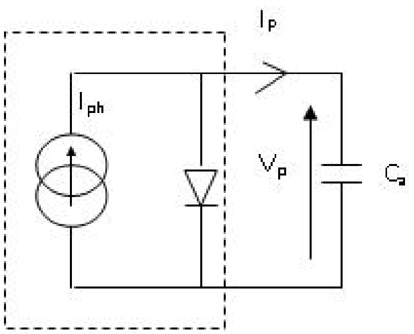
Figure. 1. Equivalent schema of a real photovoltaic cell

$$I_P = I_{Ph} - I_S[\exp(V_P/V_T) - 1] \qquad (2)$$

Where $V_T = \frac{nK_BT}{q}$ is the thermodynamic potential, I_{Ph} is the photocurrent of the PV cell proportional to illumination, I_S is the diode reverse saturation current, q is the electron charge (1,6.10 $^{-19}$ c), K_b is the Boltzman constant given as flow: (1.38.10 $^{-23}$ j/°k), T is the junction temperature in Kelvin degree, n is the ideal factor of the photovoltaic cell. The term $I_s[\exp(V_P/V_T) - 1]$ is the darkness diode current noted I_D.

2.2. Bond-graph modelling of the photovoltaic source

The PV generator has a non-linear current-voltage (I-V) characteristic. This one is characterized by an optimal operating point corresponding to the maximum power delivered by the PV generator. To simulate (I-V) characteristic, we use the bond-graph model represented in figure.2.



(a)

(b)

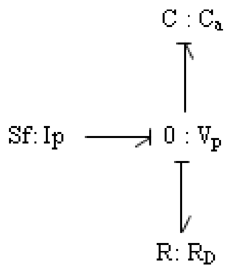
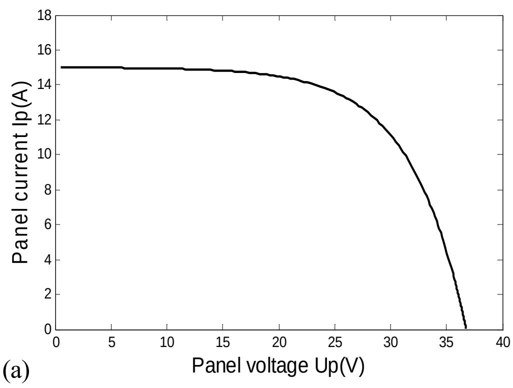
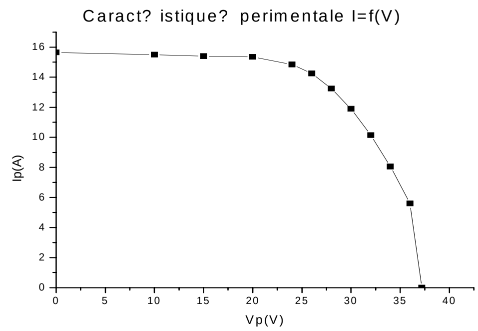


Figure. 2. Equivalent scheme of simplified PV array model (a) and its Bond graph model (b)

In order to test the theoretical model, we had compared the experimental (I-V) characteristic of the PV array to the corresponded of BG simulated one. The two curves are shown in figure.3.



(a)



(b)

Figure. 3. Simulated (a) and experimental (b) (I-V) characteristic of the PV array.

2.3. Bond graph modelling of the battery and charge regulator

The storage device (load acid batteries) is difficult to characterise and several models are used in literature [2][3][5]. Nevertheless, some of these models require information on battery parameters, which are not easily obtained. The photovoltaic generators present a limited and fluctuating energy source. For that, batteries allowing the storage of energy at illumination period are used. The accumulators are characterized by the state of charge Q, the f.e.m $V_a(Q)$ and internal resistance R_a. There are several alternatives of battery modelling. We retain that presents an electric model relating to the lead-acid batteries. For an ideal model, the battery is represented by a simple voltage source E_b in series with a resistance R_b (with R_b is the internal resistance of the battery) and a storage capacity C_b to model the effect of charge and discharge of the battery [3].

The model parameters are deduced from the current-voltage characteristics during the battery charge and discharge. figure.4 depicts the equivalent electric schema of the energy components. The corresponding bond-graph model is represented in figure.5. The bond-graph model simulations are illustrated by figure.6 [10][11].

Where U_b is the battery voltage, I_b represents the battery current, V_P is PV panel voltage, I_P is the panel current, and I_{ch} is the load current.

In this work we modelled a charge regulator, which is assimilated to two switches in the PV generator circuit disposed on both sides of the battery. The charge programme establishes operates the switches according to the battery charge state and the energy availability (solar illumination).

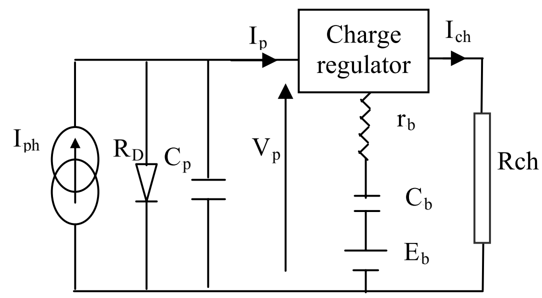


Figure. 4. Complete electric diagram of the energy components

The order of the switchers must hold in account the sense of battery current (charge or discharge phase). For the correct operation of the battery, the regulator developed maintains the battery terminal voltage between two limits. The switch model is developed in [10] [22].

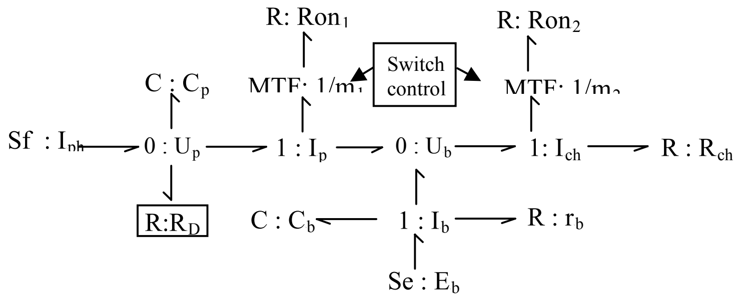


Figure. 5. Bond-graph model of the energy components

In the bond-graph model, the battery is modelled by an effort source $Se = E_b$ in series with a resistance $R : r_b$ and a capacity $C : C_b$, supplied with a photovoltaic source (already presented). The charge of the battery from PV generator and the discharge towards a receptor is controlled by a charge regulator. The last is assimilated for two switches, put in series on both sides of the battery, allowing to limit the over charge and the discharge of the battery. The switches are modelled by modulated transformer MTF in serial with resistive element $R : R_{on}$. These elements are controlled by a program pre-established depending on the battery state and the PV source. The simulation of the BG model is presented by figure.6.

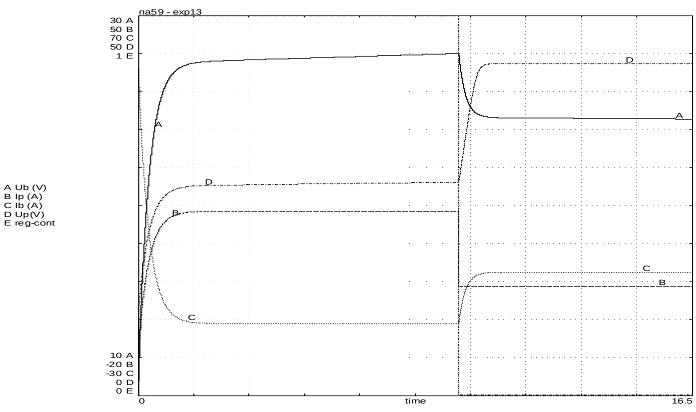


Figure. 6. Simulation of the Bond-graph model of the energy components

From simulations of figure.6, we have distinguished the charge and discharge phases of the battery between two limits (U_{bd} and U_{bc}). The battery voltage is the indicator of state of charge. According to this state the regulator commutates between two phases, where the battery current change the sign panel current joints zero and the panel voltage (V_p) towards the panel open circuit value (V_{po}).

2.4 The bond graph modeling of DC/DC converter

The DC/DC converter model

When the PV generator is directly connected to the load, the system will operate at the intersection of the $I-V$ curve and load line, which can be far from the maximum power point MPP. The converter consists of power components and control circuit. A control algorithm permits to assure maximum output power. The MPPT (Maximum power point tracking) controller used in our case is based on a boost converter. The equivalent schema of DC/DC converter is presented by figure.7.

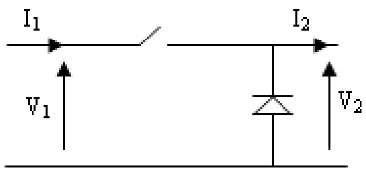


Figure. 7 Schema of the buck converter

3.1 The bond graph modeling of DC/DC converter

This method supposes the ideal switches and gives indirectly the average models appropriate to the various static inverters which permit to deduce easily the bond-graph model. For the case of the boost converter, the average values of electric parameter are given by equation (3) and (4) [2][6][22].

$$I_1 = \frac{1}{T}\int_0^{\rho} i_1(t).dt + \frac{1}{T}\int_{\rho T}^{T} i_1(t).dt = \delta I_2 \qquad (3)$$

$$V_2 = \frac{1}{T}\int_0^{\delta} v_2(t).dt + \frac{1}{T}\int_{\delta T}^{T} v_2(t).dt = \delta V_1 \qquad (4)$$

The BG model corresponding to the DC/DC converter developed by [2][22] is illustrated in the figure.7.
The complete BG model of the photovoltaic source is obtained by associating the models developed previously. The global model and the bond-graph model are respectively represented by the figure.9 and figure.10.

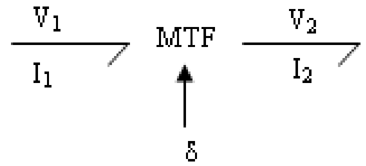


Figure. 8. The bond-graph model of boost converter

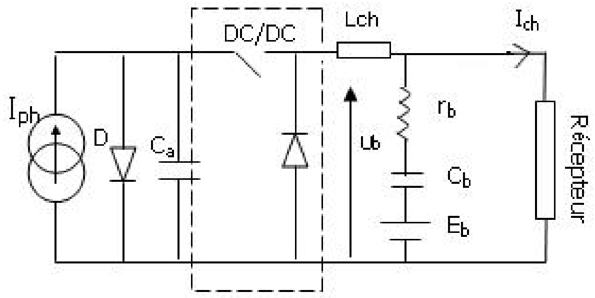


Figure. 9. Complete electric schema of the solar energy supply

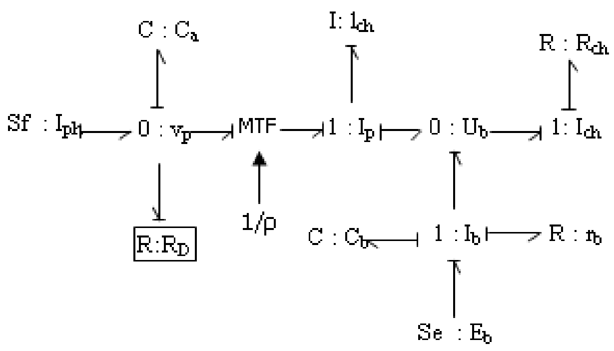


Figure. 10. Global bond-graph model of photovoltaic system

3. Non linear control law

The main objective is to charge batteries, it consist to maximize the power absorbed by the batteries [7][8]. The control law can be determined by an analytical method or directly from the B.G model. In this paper we will exploit the B.G model to determine the control law, this method includes five stage [8][9]. In what follows we will present a study of the input output linearization control law

The control of a broad class of non-linear systems can have a linear input-output behaviour by choosing a nonlinear control law per state return. We point out the theory of this control for the monovariable case [12] [5]. We consider the monovariable model with single output:

$$\dot{x} = f(x) + g(x)u \qquad y = h(x) \tag{5}$$

Where $x \in R^n$, $u \in R^m$, $f(.)$ et $g(.)$ are two fields of vectors of R^n By deriving y we obtains:

$$\dot{y} = \mathrm{L_f\ h + L_g\ h\ u} \quad \dot{y} = L_f h + L_g h\ u \tag{6}$$

Where $L_f h$ et $\mathrm{L_g\ h}$ $L_g h$ respectively indicate the Lie derivation of h in the direction of vectors fields f and g.

$$L_f h(x) = < dh, f > = \sum_{j=1}^{n} \frac{\partial h}{\partial x_j} f_j(x)$$

$$L_g h(x) = < dh, g > = \sum_{j=1}^{n} \frac{\partial h}{\partial x_j} g_j(x) \tag{7}$$

If $L_g h(x) \neq 0, \forall x \in R^n$, The control low has the following form:

$$u = \alpha(x) + \beta(x)v \tag{8}$$

Where $\alpha(.)$ and $\beta(.)$ are two function of R^n
This law is given by:

$$u = \frac{1}{L_g h}(-L_f h + v) \tag{9}$$

Thus leading to the linear system:

$$\dot{y} = v$$

If $L_g h(x) \equiv 0$, we derives (5) to have:

$$\ddot{y} = L_f^2 h + (L_g L_f h)u \tag{10}$$

With $L_f^2 = L_f(L_f h)$ and $L_g L_f h = L_g(L_f h)$

As previously, If $L_g L_f h \neq 0$, $\forall x \in R^n$ the control law:

$$u = \frac{1}{L_g L_f h}\left(-L_f^2 + v\right) \tag{11}$$

In a way more general, if r is the smallest entirety such as $L_g L_f^2 h \equiv 0$ for $i = 0, \ldots, r-2$

And $L_g L_f^{r-1} h(x) \neq 0, \forall x \in R^n$,

then the control law is written:

$$u = \frac{1}{L_g L_f^{r-1} h}\left(-L_f^r h + v\right) \tag{12}$$

Giving:

$$y^{(r)} = v$$

The number of derivation of the output necessary to reveal the input is known as relative degree of the model, extension of the definition of the relative degree into linear [14].
The diagram block of a control system by linearization input-output by return of state is as follows:

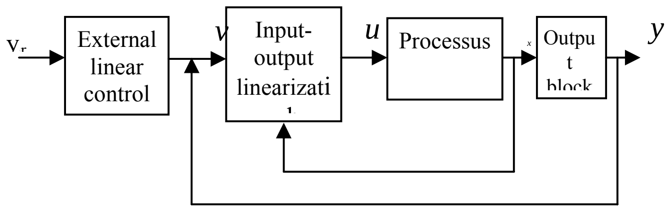


Figure. 11 : diagram block of a controller process by linearization input-output by return of state

Once the linearization is achieved, several control method can be carried out such as the placement of pole, the reference model .... etc
By using the input-output linearization by state return, the dynamic of a nonlinear system are broken up partly external (input-output) and an internal part (unobservable). Since the external part makes up of a linear relation between y and v (or per equivalence the canonical form of commandability between y and u), it is easy to conceive input v, where the output has the

desired behaviour. It remains to know if the interns dynamic well will behave (if the internal states will remain limited). The interns stability for nonlinear systems was treated in various work [15][16]. The essential definitions and results are as follows:

- **Définition 1 :**

System (5) have a relative degree r if:
$L_g h(x) = L_g L_f h(x) = \dots L_g L_f^{r-2} h(x) = \mathbf{0}$ and $L_g L_f^{r-2} h(x) \neq \mathbf{0}$ $\forall x \in R^n$.

The model (5) have a relative degree r if each $x \in R^n$ the output requires r derivations before revealing the control in (6).

If a system has a relative degree r, there is easy to check that each $x_0 \in R^n$ there is a vicinity u_0 of x_0 such as the change of co-ordinates for the state defined by:

$$\begin{aligned} T_1 &= z_{11} = h(x) \\ T_2 &= z_{12} = L_f h(x) \\ &\vdots \\ T_r &= z_{1r} = L_f^{r-1} h(x) \end{aligned} \qquad (13)$$

With $dT_1(x) g(x) = 0$ for $i = r+1 \dots n$ is a diffeomorphism

If we consider $Z_2 = (T_{r+1} \dots T_n)^T$,the equation (5) can be written in the following normal canonical form:

$$\begin{aligned} \dot{z}_{11} &= z_{12} \\ &\vdots \\ \dot{z}_{1r-1} &= \dot{z}_{1r} \\ \dot{z}_{1r} &= f_1(z_1, z_2) + g_1(z_1, z_2) \\ \dot{z}_2 &= \psi(z_1, z_2) \end{aligned} \qquad (14)$$

$$y = z_{11} \qquad (15)$$

In (14) $f_1(z_1, z_2)$ represent $L_f^r h(x)$ and $g_1(z_1, z_2)$ represent $L_f^{r-1} h(x)$. Now if $x = 0$ is a balance point of the system below ($f(o) = 0$ and $h(0) = 0$), then the dynamics (16) are the zeros dynamics.

$$\dot{z}_2 = \psi(0, z_2) \qquad (16)$$

These dynamics are the dynamic ones made unobservable by the state return. Indeed the law linearization by state return is the nonlinear equivalent of the poles zero placement in loop closed of the model, in order to make them unobservable [15].

It is noted that the subspace:

$$L = \{x \in U^0 : L_f h(x) = \cdots L_f^{r-1} h(0)\} = \{x \in U^0 : z_1 = 0\}$$

Can be invariant while choosing:

$$u = \frac{1}{g_1(z_1, z_2)} (-f_1(z_1, z_2) + v) \qquad (17)$$

The dynamics (16) are the dynamics on this space. The system (5) is known as minimal of phase if the dynamics of the zeros are asymptotic stable as indicates it the following definition:

- **Définition 2** : [16]

A nonlinear system is known as asymptotically phase minimal if the dynamics of the zeros is asymptotically stable.

The dynamic interns associated with the linearization input-output, corresponding to the last equations: normal form, generally depend on the output. For that we defines an intrinsic property of the nonlinear system consider the system internal dynamics when the entry makes it possible to maintain the output in zeros. To suppose the null output implies that all its derivatives are null. For that the dynamic interns correspond to the model where the zeros dynamic describe the movements on a surface M_0 of $n - r$ dimension defined by $Z_1 = 0$ [14].

4. Determination of the control law directly on Bond Graph

The control law can be determined directly from the B.G model, this method includes five stage [8][9].

The photovoltaic state equation can be put in the following form (5).

$$\begin{bmatrix}\dot{p}_{ch}\\ \dot{q}_{cp}\\ \dot{q}_{cb}\end{bmatrix}=\begin{bmatrix}-r_b/l_{ch} & \rho/c_p & -1/c_b\\ -\rho/l_{ch} & -1/R_D c_p & 0\\ 1/l_{ch} & 0 & 0\end{bmatrix}\begin{bmatrix}p_{ch}\\ q_{cp}\\ q_{cb}\end{bmatrix}+\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}E_b\\ I_{ph}\end{bmatrix} \quad (18)$$

Stage 1: Bond-graph model with standard causality

The minimal dynamic way or output-input way (ρ, v_p), having only one integrator. The number of this integrator gives the relative output-input degree: $r = 1$.

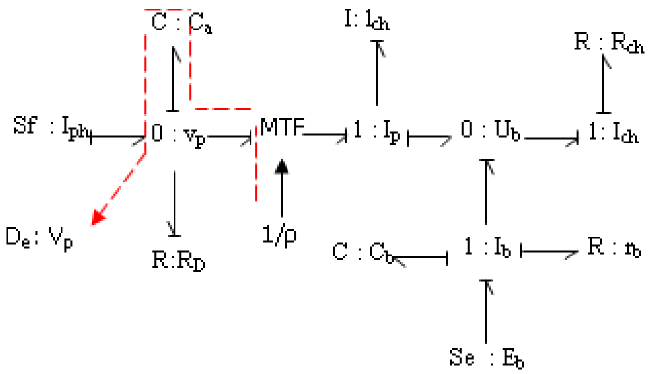


Figure.12. Bond-graph model with the minimal dynamic way

Stage 2: development of the reverses model

The method is based on the causal inversion input-output for the B.G of the system; it consists to deduce the static and dynamics input-output control law directly on bond-graph model. For the design of the control system, it is often useful to determine the input from the desired output. This is obtained by the inversion of the system dynamics where the input is replaced by the output, which corresponds for a control of the opposite system. To determine the opposite model, the bond graph technique was extended by the introduction of the concept of bi causality [13].

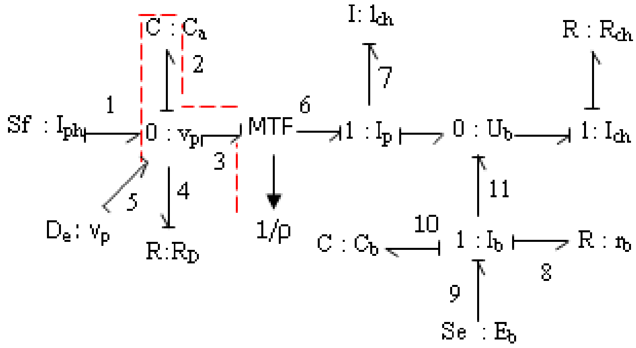


Figure.13. The opposite bond-graph model

The currents f_3 et f_6 became the output of the transformer
With:

$$m = \frac{1}{\rho} = \frac{f_3}{f_6} \quad (19)$$

From this equation we can deduce the control law : U

$$U = \rho = \frac{f_3}{f_6} \qquad \begin{cases} e_6 = \rho e_3 \\ f_3 = \rho f_6 \end{cases} \quad (20)$$

Stage 3: Deduction of the minimal dynamic equation

We deduce a mathematical model reverses called minimal dynamic equation. The equation is obtained while reading the bond graph model with opposite causality.
The cyclic ratio of the boost converter is the input of the control law U .
The state vector is $x = [p_{ch}\ q_{cp}\ q_{cb}]^T$

The output is the voltage of the generator: $y = v_p$

$$f_6 = \frac{p_{ch}}{l_{ch}}, \ f_4 = \frac{e_5}{R_D}, \ \dot{q}_2 = c\frac{dv_p}{dt} = f_2 \quad (21)$$

According to (20) and (21) we obtain:

$$f_3 = I_{ph} - I_s[\exp(v_p / v_{Tt}) - 1] - c\dot{v}_p$$
$$U = \frac{l_{ch}}{p_{ch}}[I_{ph} - I_s(\exp v_p / v_T) - 1) - \frac{c\dot{y}l_{ch}}{p_{ch}} \quad (22)$$

Stage 4: development of control law

From the dynamic equation minimal, we replace $\dot{y}^{(r)}$ $(r = 1)$ by a new control input v; the input-output relation system (with feed-back) becomes linear according to the equation: $y^r = \dot{y} = v$

The linearization static law is:

$$U = \frac{l_{ch}}{p_{ch}}[(-I_s \exp(q_c / cv_T) - 1) + I_{ph}] - c\frac{l_{ch}}{p_{ch}}v \quad (23)$$

The feedback linearization control law is inserted in PV voltage control loop in order to reach the optimal voltage. This objective can be achieved by a simple control law v : $v = k(y_d - y)$

In this case, the control transformed the system into "integrating block", a proportional "P" regulator is suitable.

We can make the measurable sizes:

$$U = \frac{1}{I_b}[(-I_s \exp(v_p / v_T) - 1) + I_{ph}] - \frac{c}{I_b}v \quad (24)$$

The diagram of the system is given by the following figure.

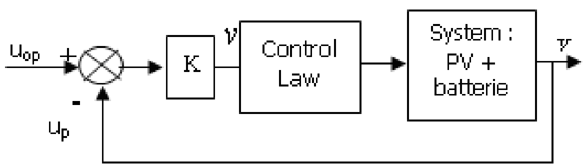


Figure.14. Diagram of the system with control law

This control law made two states unobservable (q_{ch}, p_{ch}) from the new control v. According to the nonlinear control theory, this variety represents the dynamics of the zeros of the system whose study of internal stability is essential

Stage 5: study of stability

The dynamics of the zeros is obtained by imposing $y = 0$, all bonds attached of "0" junction is cancelled, consequently the power is cancelled. We apply the second method of lyapunov to the bond-graph to analyze the stability of dynamics of the zeros. We can choose the sum of the energies stored in the elements of storage I et C like function candidate of lyapunov [9].

$$E(t) = V = \sum_{i=1}^{n_i} \varepsilon_i(p_i) + \sum_{j=1}^{n_j} \varepsilon_{n_i+j}(q_j)$$
$$V = \frac{1}{2}(\frac{p_{ch})^2}{l_{ch}} + \frac{(q_{cb})^2}{c_b}) \quad (25)$$

The derivative of this energy represents the difference between the power delivered by the source and the consumption by the dissipative elements.

$$\dot{V}(x) = \sum_{i=1}^{n_i} P_1 + \sum_{j=1}^{n_j} P_{n_i+j} = P_1(t) - P_2(t)$$
$$\dot{V}(x) = -P_2(t) = -[r_b(\frac{p_{ch}}{l_{ch}})^2] < 0 \quad (26)$$

Energy is decreasing is cancelled in the origin, the equation associated is asymptotically stable, therefore the system is minimal of phase.

4. Simulations and results

After elaborating the BG model of the system and the control law, different simulations have been performed to test the work elaborated. The aim to ensure the performance of the control law, we verified the reaching point depending on the climatic condition where the terminal power on the battery is maximal. The Fig 15 represents the BG model with feedback linearization input output control. The first simulation (figure16) consists in a simple simulation where we consider the PV source, the storage batteries and control law elaborated without the charge regulator. From simulation we distinguish that the control law is able to stabilise the system on the desired output power. We notice that the regulator developed is well adapted where the output follows the input. Since the result of simulation is favourable we can extend simulation and establish the charge regulator of the battery. From simulation of figure 17 is very interesting to distinguish the charge and discharge phases of the battery between two limits (V_{ad}

and V_{ac}). The battery voltage is the indicator of charge state of the battery. According to this state the regulator commutates between two phases, where the battery current change the sign and panel current joins zero. The control law stabilise the system on the desired output power and the output follows the input.

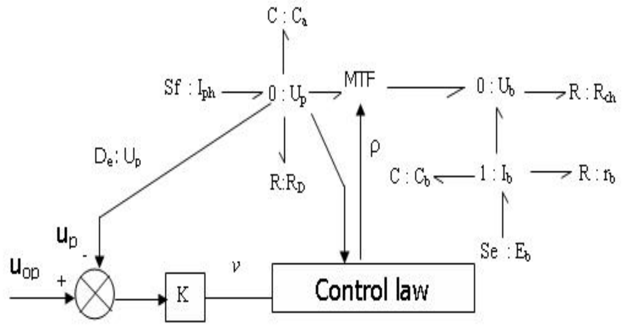


Figure 15. The BG model with feedback linearization input output control

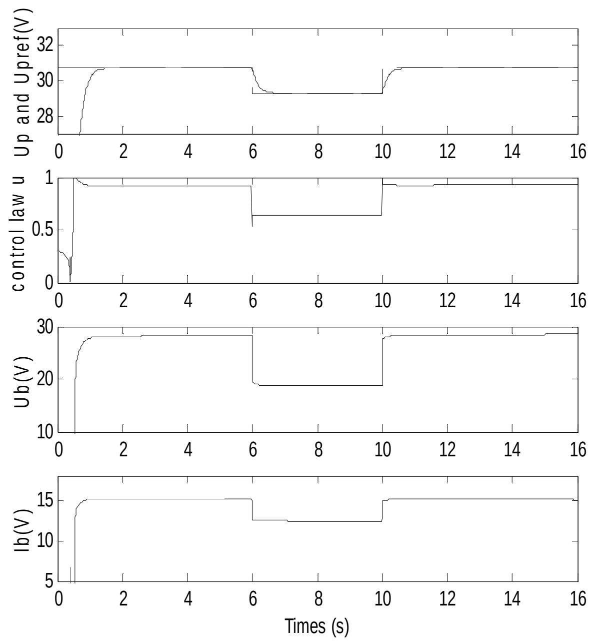


Figure.16. Simulation of model BG of the system with state feedback linearization control

5. Conclusion

The pilot unit, the object of our study, consists of a photovoltaic generator, storage battery with charge regulator, Maximum power point tracking (MPPT) and the loads. With these varied elements, the modelling of this pilot unit becomes complex. For that, we proposed a unified approach of modelling based on graphic technique known as bond-graph. This technique is systematic and has a sufficient flexibility to be able to introduce various components into the system and to establish a nonlinear control law.
In this paper an electric model of the photovoltaic source is presented and the complete BG model for different elements of the system is elaborated. This model was used to design a state feedback linearization input output control law. A non linear approach has been proposed to control the loading of a battery and exploit the maximum of energy delivered by the PV panel. In this paper we have exploit the B.G model to determine the control law, (this method includes five stages). Reliable simulation results are presented to demonstrate the validity of the proposed control approach.

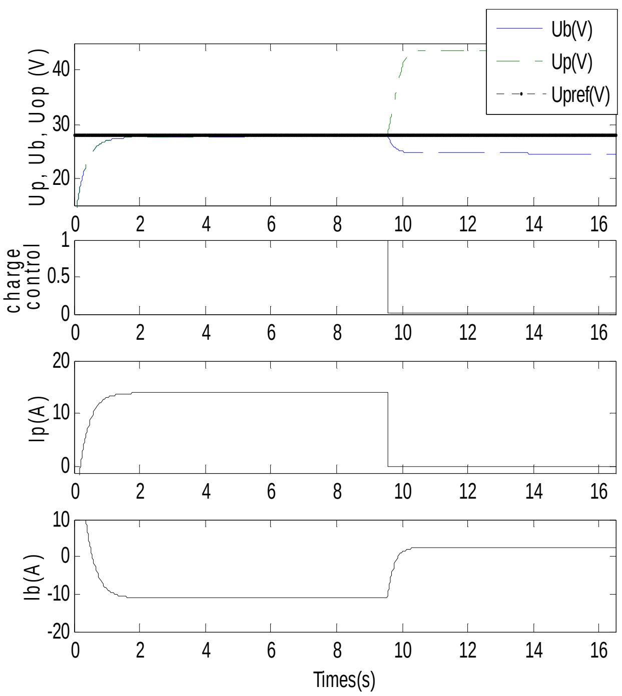


Figure. 17. Simulation of model BG of the system with charge regulator and state feedback linearization input-output control law.

References

[1] B.Allard, H Morel,Ph Lautier, and J.M.Retif, Bong-graphs for averaged modelling of power electronic converters. Proceeding of the SCS International Conference on Bond-graph Modeling (ICBGM' 97). Phoenix, USA, Vol 29, N° 1, 201-206.

[2] R.Andoulsi, A. Mami, G. Dauphin-Tanguy, M. annabi, Modelling and simulation by Bond Graph technique of a DC motor fed from a photovoltaic source via MPPT boost converter. Proceeding of CSSC'99, pp 4181-4187.

[3] Bogdan S.Borouy, Zied M. Salameh: Dynamic reponse of a stand-Alone wind energy Conversion System with battery energy storage to a wind Gust. IEEE transaction on Energy Conversion. Vol 12.N°1,marsh1997.

[4] J.N. Ross, T. Markvart and WHE, Modeling battery charge regulation for a stand-alone photovoltaic system, Solar Energy vol.69 N°3, issue 2000,181-190.

[5] B.S.Borowy and Z.M.Salameh, Dynamic response of a stand-Alone wind energy conversion system with battery storage to a wind gurst, IEEE Transaction on Energy conversion vo1. 12, issue 1 Marsh 1997, 73-75.

[6] V. Mahout,"On the robustness of the flatcontrol," ISC3, juin 2003.

[7] H. SiraRamirez and Silva Navarro G.,"Regulation and traking for the overage boost converter circuit: a generalized proportional integral approach," Int. Journal of control, vol. 75, pp. 988-1001, 2002.

[8] Bertrand, J.C. Sueur, G. Dauphin-Tangy. Bond Graph for Modelling and Control Structural Analysis Tools for the design input output Decoupling State Feedbacks. Proceding ICBGM'1997/Simul.Series 29:1.

[9] Junco. Sergio, Linéarisation exacte entrée-sortie et stabilité de la dynamique des zeros directement sur bon graph des systèmes non linéaires. Actes de CIFA 2000, Première conférence Internationale Francophone d'automatique, 4-7 juillet 2000.Lille, France.

[10] Junco. Sergio, Lyapunov's second method and feed-back stabilization directly on Bond Graph, Proceeding of ICGBM'01, 2001, pp 86-98.

[11] Zitouni.N, Andoulsi.R, Sellami.A, Mhiri.R," Bond graph modelling of a UV water Disinfection pilot unit fed by a photovoltaic source". JTEA'2006, 12-14 may 2006 à Hammamet, Tunisie.

[12] P.J. Gawthrop, D.J. Wagg, S.A. Neild, Bond graph based control and substructuring, Simulation Modelling Practice and Theory 17 (2009) pp 211–227.

[13] N. Yadaiah, N. Venkata Ramana, Linearisation of multi-machine power system: Modeling and control – A survey, Electrical Power and Energy Systems 29 (2007) 297–311

[14] Roger F. Ngwompo, Peter J. Gawthrop, Bond graph-based simulation of non-linear inverse systems using physical performance specifications, Journal of the Franklin Institute 336 (1999) 1225}1247

[15] J. J. E. Slotine W.Li, Applied nonlinear control, Printice-hall international editions. Englewood Cliffs, New Jersey 1991.

[16] C Kravaris, Input/output linearization: A nonlinear analog of placing poles at process zeros. AICHE Journal, Vol 34, N°11, November 1988, pp 1803-1812.

[17] A. Isidori, A tool for semi-global stabilizationof uncertain non-minimum-phase nonlinear systems via output feed-back. IEEE trasaction on automatic control, Vol 45.N° 10 October 2000, pp 1817-1827.

[18] I.H. Atlas and A.M.Sharaf, "Anouvel maximum power fuzzy logic controller for photovoltaic solar energy systems", Renewable energy 2007.

[19] Nopporn Patcharaprakiti, Suttichai.P and Yosanai.S,"Maximum power point traking using adaptative fuzzy logic control for grid-connected photovoltaic system", Renewable energy 30 (2005), pp 1771-1788.

[20] R.Akkaya, A.A.Kulaksiz and Ö. "Aydogdu, DSP implementation of a PV system with GA-MLP-NN based MPPT controller supplying BLDC motor drive", Energy Conversion and Management 48 (2007), pp 210-218.

[21] N.Hamrouni, M.jraidi, A.Cherif, A.Dhouib, "Measurement and simulation of a PV pumping systems parameters using MPPT and PWM control strategies", IEEE MELECOM 2006.

[22] D.Mezghanni, R. Andoulsi, A. Mami, G. Dauphin-Tanguy, " Bond graph modelling of a photovoltaic system feeding an induction motor-pump" Simulation Modelling Practice and Theory 15 (2007) 1224–1238.

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