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A Nonlinear Observer Design for P-Cells Chopper

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Abstract – This paper deals with an observer design for a P-Cell Chopper. The goal is to reduce drastically the number of sensors in such system by using an observer in order to estimate all the capacitor voltages. Furthermore, considering an instantaneous model of a p-cell chopper, an interconnected observer is designed in order to estimate the capacitor voltages and some parameters of the model. This is realized by using only the load current measurement. Simulation results are given in order to illustrate the performance of such observer. To show the validity of our approach, experimental based a DSP results are presented.

Keywords: P-cell chopper, Observer design, Interconnected observer

1. Introduction

The power electronics knows important technological developments. This is carried out thanks to the developments of the semiconductor of power components but also of new systems of energy conversion. Among these systems, multicellular converters are based on the association in series of the elementary cells of commutation. This structure appeared at the beginning of the 90's [14], makes it possible to share the constraints in tension and/or while running in high voltages installations by the cells of commutation series-connected and also to improve the harmonic contents of the forms of waves.

To benefit as well as possible from the large potential of the multicellular structure, research then went in various directions. Initially models were developed to describe their instantaneous behaviors [4], harmonic [6] or averaging [1] and [2]. These various models were used at the base for the development of laws of open-loop control [12] and closed-loop, [21]. Modelling is a very important phase for the synthesis of the laws of order and the observers.

In this article, we developed new observer for p-cellular converters. For that, the instantaneous model of the p-cell chopper is considered in order to design an observer estimating the flying capacitor voltage. The proposed observer design is based on the class of nonlinear systems which can be written in a form of affine state systems, for which the problem of state observer design has been studied. This class of observer is based on the excitation condition in order to guarantee the convergence of it.

The paper is organized as follows: In the first section, some definitions and notation used for instantaneous model of p-cell chopper are introduced. In section 2, the properties of the observer p-cell chopper is given. The observer design for this class of converter using the instantaneous model is presented in the section 3. The interconnected observer design is presented, where a 5 cell chopper converter is considered in order to estimate the capacitor voltages which are unmeasurable. In section 4, a 2 cell chopper converter with unknown parameters is analyzed.

In this case, an observer design is presented in order to estimate the capacitor voltage and the voltage of the source and the resistance which are assumed unknown and constant. Simulations and experimental results are shown in order to illustrate the performance of the proposed observer.

Finally, some conclusions are given.

2. P-Cell Converter Model

Throughout the paper, the p-cell converter connects in series p elementary cells and a passive load R and L as illustrated in Fig 1.

Each switching cell is controlled by a binary input signal $S_k(t)$ for k = 1,… p.

This signal $S_k(t)$ is equal to 1 when the upper switch of the cell is conducting and 0 when the lower complementary switch of the cell is conducting. The mathematical model describing

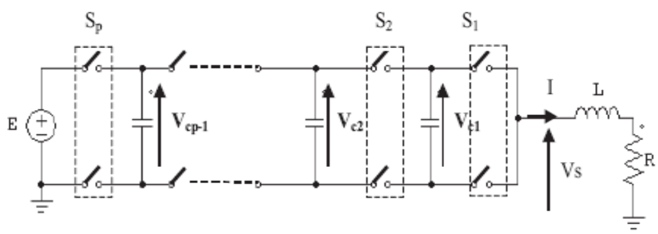

Fig. 1. A p cells converter.

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$$\sum_{pcell}:\begin{cases}\dfrac{dI}{dt}=-\dfrac{R}{L}I+\dfrac{E}{L}S_p-\dfrac{v_{cp-1}}{L}(S_p-S_{p-1})\ldots-\dfrac{v_{c1}}{L}(S_2-S_1)\\ \dfrac{dv_{c1}}{dt}=\dfrac{1}{c_1}(S_2-S_1)I\\ \dfrac{dv_{c2}}{dt}=\dfrac{1}{c_2}(S_3-S_2)I\\ \vdots \qquad \vdots \qquad \vdots\\ \dfrac{dv_{cp-1}}{dt}=\dfrac{1}{c_{p-1}}(S_p-S_{p-1})I\\ y=I\end{cases} \tag{1}$$

Where v_{ck} is the k^{th} flying capacitor voltage and I is the output load current, which is the only measurable output. c_k for k = 1, …, p; are the capacitors, E is the voltage of the source, R is the resistance and L is the inductance.

Now from the instantaneous state model of the p-cell converter given in (1), we will analyze the observability properties of such system in order to construct an observer. It is well known that the observability of a nonlinear system depends on the applied input, and a study of different classes of inputs which render the system observable or unobservable is given in [9], [10].

Rewriting the model (1) in a state affine form, we have:

$$\sum \quad : \quad \begin{cases}\dot{X}=\overline{A}(u)X+\overline{B}(u)\\ y=\overline{C}X\end{cases} \tag{2}$$

where $X = (I, v_{c1}, \ldots, v_{cp-1})$ is the state vector,
$u = \{S_1, \ldots, S_p\}$ is the input sequence applied to the converter,

$$\overline{A}(u)=\begin{pmatrix}-\dfrac{R}{L} & -\dfrac{1}{L}(S_2-S_1) & \ldots & -\dfrac{1}{L}(S_p-S_{p-1})\\ -\dfrac{1}{c_1}(S_2-S_1) & 0 & \ldots & 0\\ \ldots & \ldots & \ldots & \ldots\\ -\dfrac{1}{c_{p-1}}(S_p-S_{p-1}) & 0 & \ldots & 0\end{pmatrix}$$

$$\overline{B}(u)=\begin{pmatrix}\dfrac{E}{L}S_p\\ 0\\ \vdots\\ 0\end{pmatrix} \quad \text{and} \quad \overline{C}=(1, 0, \ldots, 0)$$

3. Observability Study

Regarding the instantaneous model of the multi-cell converter (2), we can see that there are several operating switching modes (S_k, S_{k+1}) which render the system unobservable for the following operating switching modes.

$$(S_k, S_{k+1}) = (1, 1) \quad \text{and} \quad (S_k, S_{k+1}) = (0, 0) \quad \text{for} \quad k = 1,\ldots, p-1$$

These operating switching modes are not affected by the capacitor voltages. However, these cases occur only for a part of control sequence. If it occurs for all the control sequences then it is not of physical interest because they represent particular situations in which the cell chopper is not operating.

For any sequence of the corresponding input $u = \{u_1, \ldots, u_{p-1}\}$, where $u_k = S_{k+1}-S_k$, is applied to the system (1), the control sequence becomes sufficiently periodic. Furthermore, assuming that the current I is the only measurable variable of the system (2) from the observability rank condition then it can be written as:

It is clear that the system is not of the full rank, i.e. the system is not observable. In order to overcome this difficulty, we consider a new representation of the multi-cell converter, which is constituted of a set of 2D subsystems. These subsystems are represented as an interconnected structure such as a whole system. An analysis of each subsystem observability is required and is given in the following section.

4. Observer Design for P Cell Chopper

In this section, the design of p-1 interconnected observers for p cell chopper is given. We will consider a different representation of system (1) such that the original system can be splitted into a suitable set of p-1 subsystems for which it will be possible to design an observer for estimating the capacitor voltages v_{cj}, j=1, …, p-1. Next, considering that the system (1) can be splitted into p-1 interconnected subsystems of the form:

$$\sum_k : \begin{cases}\dfrac{dI}{dt} = -\dfrac{R}{L}I+\dfrac{E}{L}S_p-\dfrac{1}{L}\sum\limits_{j=1}^{p-1}(S_{j+1}-S_j)\, v_{cj}\\ \dfrac{dv_{ck}}{dt}=\dfrac{1}{c_k}(S_{k+1}-S_k)\, i\\ y = I\end{cases}$$

The above mentioned system can be represented, for k=1, .., p-1, in a compact form as:

$$\sum_k : \begin{cases}\dot{X}_k = A_k(u_k)X_k + B_k(\overline{u}_k, \overline{X}_k)\\ y = C_k X_k\end{cases} \tag{3}$$

Where $X_k=(I, v_{ck})^T$ is the state vector of the subsystem (3),

$X = (I, v_{c1}, \ldots, v_{cp-1})^T$ is the state vector of the system (1), $\overline{X}_k = (v_{c1}, \ldots, v_{ck-1}, v_{ck+1}, \ldots, v_{cp-1})^T$, $u_k=(S_{k+1}-S_k)$, for k=1, …, p-1; and $\overline{u}_k = (u_1, \ldots, u_{k-1}, u_{k+1}, \ldots, u_p)^T$, are the inputs. Furthermore, $y = C_kX_k=I$, is the output of the subsystem (3) with $C_k=(1\ 0)$; for k=1, …, p-1; and

$$A_k(u_k) = \begin{pmatrix}-\dfrac{R}{L} & -\dfrac{(u_k)}{L}\\ \dfrac{(u_k)}{c_k} & 0\end{pmatrix} \tag{4}$$

and for k=1, 2, …, p-1;

$$B_k(\bar{u}_k,\ \bar{X}_k) = \begin{pmatrix} -\frac{1}{L}\sum_{\substack{j=1\\ j\neq k}}^{p-1}(S_{j+1}-S_j)v_{cj} + \frac{E}{L}S_p \\ 0 \end{pmatrix} = \begin{pmatrix} -\frac{1}{L}\bar{u}_k^T\ \bar{X}_k + \frac{E}{L}S_p \\ 0 \end{pmatrix} \quad (5)$$

It is clear that for $u_k=0$, the system becomes unobservable. However, each subsystem k^{th}, which is of dimension 2 is observable for an appropriate input u_k and it's rank is equal to 2. In order to estimate the unmeasurable variables, no feedback is applied to excite the converter as it has been proposed in other works. In this work, we propose a similar concept which is a well-known concept of regularly persistent input (see appendix). More precisely, a regularly persistent input is applied to the system which allows exciting it sufficiently to obtain the information necessary to reconstruct the unmeasurable variables by means of an observer. If the input is not sufficiently persistent then it is not possible to reconstruct the state of the system from the measured output. The observer works correctly by avoiding the applied input.

The function $B_k(\bar{u}_k,\ \bar{X}_k)$ is the interconnection term depending on inputs and states of each subsystem. The output is the current I(t); it is the same for each subsystem:

$$O_k : \begin{cases} \dot{Z}_k = A_k(u_k)\ Z_k + B_k(\bar{u}_k,\ \bar{Z}_k) - P_k^{-1}C_k^T(y_k - \hat{y}_k) \\ \dot{P}_k = -\theta_k P_k - A_k^T(u_k)P_k - P_kA_k(u_k) + C_k^TC_k \end{cases} \quad (6)$$

O_k is an observer for the subsystem (3), for k=1, 2, …, p-1; where $\theta_k > 0$, $\hat{y}_k = C_kX_k = \hat{I}$ and $P_k^{-1}C_k^T$ is the gain of the observer which depends on the solution of the second equation of (8) for each subsystem with $Z_k = (\hat{I},\ \hat{v}_{ck})^T$, $\bar{Z}_k = (\hat{v}_{c1}, ..., \hat{v}_{ck-1}, \hat{v}_{ck+1}, ..., \hat{v}_{cp-1})^T$ and $A_k(u_k)$ is given in (6)

Now, consider that the system (1) can be represented as follows:

$$\sum : \begin{cases} \dot{X}_1 = A_1(u_1)X_1 + B_1(\bar{u}_1,\ \bar{X}_1) \\ \dot{X}_2 = A_2(u_2)X_2 + B_2(\bar{u}_2,\ \bar{X}_2) \\ \vdots \\ \dot{X}_{p-1} = A_{p-1}(u_{p-1})X_{p-1} + B_{p-1}(\bar{u}_{p-1},\ \bar{X}_{p-1}) \end{cases} \quad (7)$$

Noting that the output is the current I(t) and is the same for each subsystem. The main idea of this paper is to construct an observer for the whole system (1) from the separate observer design of each subsystem (3). In general, if each (6) is an exponential observer for (3), for k=1, 2, …, p-1; then the following interconnected system can be represented as:

$$O : \begin{cases} \dot{Z}_1 = A_1(u_1)Z_1 + B_1(\bar{u}_1,\ \bar{Z}_1) - P_1^{-1}C_1^T(y-\hat{y}) \\ \dot{Z}_2 = A_2(u_2)Z_2 + B_2(\bar{u}_2,\ \bar{Z}_2) - P_2^{-1}C_2^T(y-\hat{y}) \\ \vdots \\ \dot{Z}_{p-1} = A_{p-1}(u_{p-1})Z_{p-1} + B_{p-1}(\bar{u}_{p-1},\ \bar{Z}_{p-1}) - P_{p-1}^{-1}C_{p-1}^T(y-\hat{y}) \\ \dot{P}_1 = -\theta_1P_1 - A_1^T(u_1)P_1 - P_1A_1(u_1) + C_1^TC_1 \\ \dot{P}_2 = -\theta_2P_2 - A_2^T(u_2)P_2 - P_2A_2(u_2) + C_2^TC_2 \\ \vdots \\ \dot{P}_{p-1} = -\theta_{p-1}P_{p-1} - A_{p-1}^T(u_{p-1})P_{p-1} - P_{p-1}A_{p-1}(u_{p-1}) + C_{p-1}^TC_{p-1} \end{cases} \quad (8)$$

is an observer for the interconnected system (7).

Remark 1: The proposed observer (8) works for inputs satisfying the regularly persistent condition, which is equivalent to each subsystem (3) being observable, and hence, observer (6) works at the same time while the other subsystems become observable when their corresponding input satisfies the regularly persistent condition.

Now, we will give the sufficient conditions which ensure the convergence of the interconnected observer (8). For that, we introduce the following assumptions.

Assumption 1: Assume that the input $u_k=(S_{k+1}-S_k)$, for k=1, 2, …, p-1; is regularly persistent input for subsystem (3), and admits an exponential observer (6). The estimation error, defined as $\varepsilon_k=Z_k-X_k$, is bounded.

Assumption 2: The term $B_k(\bar{u}_k,\ \bar{X}_k)$ does not destroy the observability property of the subsystem (3), under the action of the regularly persistent input $u_k=(S_{k+1}-S_k)$, for k=1, 2, …, p-1. Moreover, $B_k(\bar{u}_k,\ \bar{X}_k)$ is Lipschitz with respect to k and uniformly with respect to $\bar{u}_k$, for k=1, 2, …, p-1.

The observer convergence can be proved only if the inputs u_k are regularly persistent, i.e. it is a class of admissible inputs that allows to observer the system (for more details see [12], [13]). This assumption guarantees that the observer works and its gain is well-defined, i.e. the matrices P_k, for k=1, 2, …, p-1; are non-singular (see appendix).

The following result can be established.

Proposition 1 Consider the system (1) can be represented in the form of system (7), where each subsystem (3) satisfies the assumption 1 and assumption 2, for k=1, 2, …, p-1. Furthermore, the system (8) is an exponential observer for system (7), thus the estimation error, defined as ε=Z-X, converges exponentially to zero.

Consider the system (1) can be represented in the form of system (7), where each subsystem (3) satisfies the assumptions 1 and 2, for k=1, 2, …, p-1. Then, system (8) is an exponential observer for system (7). Furthermore, the estimation error, defined as ε=Z-X converges exponentially to zero.

5. Observer 5 Cell chopper

In this section we present the proposed methodology which is applied to a model of 5 Cell Chopper converter. For that, consider the following model of 5 cell chopper

$$\sum_{5cell} : \begin{cases} \frac{dI}{dt} = -\frac{R}{L}I + \frac{E}{L}S_5 - \frac{(S_2-S_1)}{L}v_{c1} - \frac{(S_3-S_2)}{L}v_{c2} - \frac{(S_4-S_3)}{L}v_{c3} - \frac{(S_5-S_4)}{L}v_{c4} \\ \frac{dv_{c1}}{dt} = \frac{1}{c_1}(S_2-S_1)\ I \\ \frac{dv_{c2}}{dt} = \frac{1}{c_2}(S_3-S_2)\ I \\ \frac{dv_{c3}}{dt} = \frac{1}{c_3}(S_4-S_3)\ I \\ \frac{dv_{c4}}{dt} = \frac{1}{c_4}(S_5-S_4)\ I \end{cases} \quad (9)$$

Following the ideas of this original methodology, the model can be rewritten in the following form:

$$\Sigma_1 : \begin{cases} \frac{dI}{dt} = -\frac{R}{L} I + \frac{E}{L} S_5 - \frac{(S_2 - S_1)}{L} v_{c1} - \frac{(S_3 - S_2)}{L} v_{c2} - \frac{(S_4 - S_3)}{L} v_{c3} - \frac{(S_5 - S_4)}{L} v_{c4} \\ \frac{dv_{c1}}{dt} = \frac{1}{c_1} (S_2 - S_1)\, I \end{cases}$$

$$\Sigma_2 : \begin{cases} \frac{dI}{dt} = -\frac{R}{L} I + \frac{E}{L} S_5 - \frac{(S_2 - S_1)}{L} v_{c1} - \frac{(S_3 - S_2)}{L} v_{c2} - \frac{(S_4 - S_3)}{L} v_{c3} - \frac{(S_5 - S_4)}{L} v_{c4} \\ \frac{dv_{c2}}{dt} = \frac{1}{c_2} (S_3 - S_2)\, I \end{cases}$$

$$\Sigma_3 : \begin{cases} \frac{dI}{dt} = -\frac{R}{L} I + \frac{E}{L} S_5 - \frac{(S_2 - S_1)}{L} v_{c1} - \frac{(S_3 - S_2)}{L} v_{c2} - \frac{(S_4 - S_3)}{L} v_{c3} - \frac{(S_5 - S_4)}{L} v_{c4} \\ \frac{dv_{c3}}{dt} = \frac{1}{c_3} (S_4 - S_3)\, I \end{cases}$$

$$\Sigma_4 : \begin{cases} \frac{dI}{dt} = -\frac{R}{L} I + \frac{E}{L} S_5 - \frac{(S_2 - S_1)}{L} v_{c1} - \frac{(S_3 - S_2)}{L} v_{c2} - \frac{(S_4 - S_3)}{L} v_{c3} - \frac{(S_5 - S_4)}{L} v_{c4} \\ \frac{dv_{c4}}{dt} = \frac{1}{c_4} (S_5 - S_4)\, I \end{cases}$$

This set of subsystems can be represented in an interconnected compact form as follows:

$$\Sigma_i : \begin{cases} \dot{X}_i = A_i(u_i) X_i + B_i(\bar{u}_i, \bar{X}_i) \\ y = C_i X_i = I \end{cases} \quad \text{for } i = 1, \ldots, 4$$

It can be assumed that the control sequence of inputs provides the sufficient persistency to guarantee that the observer works correctly (see appendix and assumption 1). Using this assumption, an observer for the above interconnected subsystems are given by:

$$O_i : \begin{cases} \dot{\hat{Z}}_i = A_i(u_i)\hat{X}_i + B_i(\bar{u}_i, \bar{Z}_i) + P_i^{-1} C_i^T (y - \hat{y}) \\ \dot{P}_i = -\theta_i P_i - A_i^T(u_i) P_i + P_i A_i(u_i) + C_i^T C_i \end{cases} \quad \text{for } i = 1, \ldots, 4$$

Now, we show some simulation results obtained by using the proposed interconnected observer.

In order to illustrate the performance of this observer, where the estimates converge to the real states, the instantaneous converter model of 5 cells (9) is simulated, where the capacitor voltages have been considered unmeasurable. The parameters of the model were chosen as follows:

f_d=16kHz, C=40μF, L = 1mH, R=10Ω, E=1500V.

Furthermore, to carry out the simulations, the following initial conditions of the system and the observer were selected as follows:

For the system: $X_k = (I, v_{ck})^T = (0, 0)^T$ and for the observer: $Z_k = (\hat{i}, \hat{v}_{ck})$ are given as (1, 20), (1, 30), (1, 35) and (1,40) for k=1, …, 4.

The parameters θ_k, for k=1, …, 4; which are the design parameters used to control the rate of convergence of each observer, were chosen as follows: θ_1=30, θ_2=40, θ_3=50 and θ_4=60.

In Figs. 2, 4, 6, 8; we can see that the estimate capacitor voltage converges to the real variables (see estimation error in Figs. 3, 5, 7, 9). However, the simulation results were obtained such that the initial conditions of the observer and the converter were chosen in such a way to show the convergence of the observer. Hence, the value of the parameter θ_k can be increased in order to accelerate the convergence of the observer. However, it is desirable to give good initial

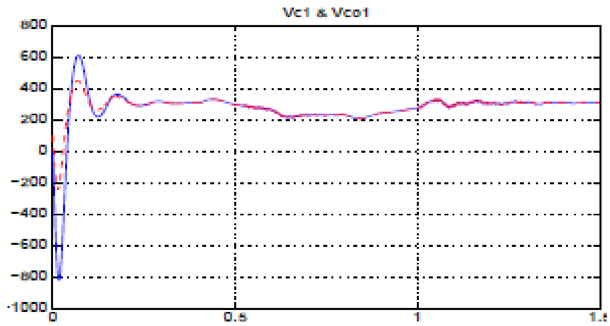

Fig. 2. Capacitor voltage *Vc*1 and its estimation.

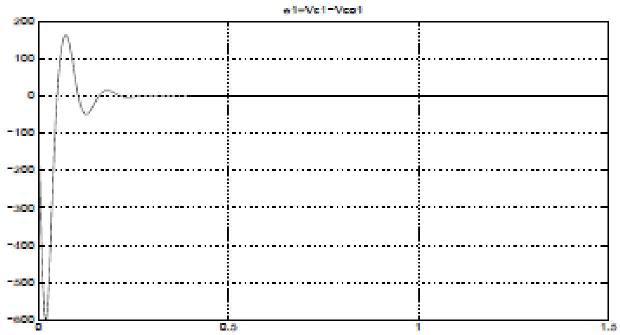

Fig. 3. Estimation error.

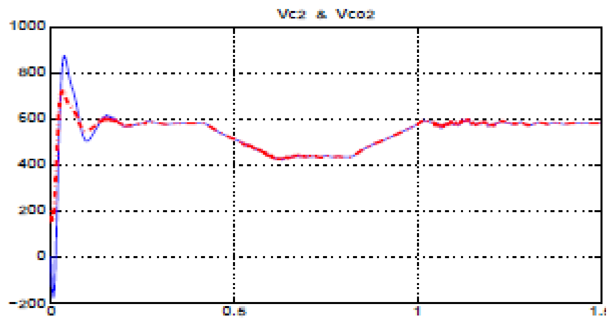

Fig. 4. Capacitor voltage *Vc*2 and its estimation.

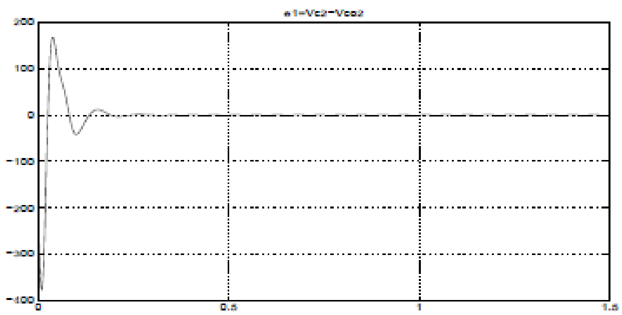

Fig. 5. Estimation error.

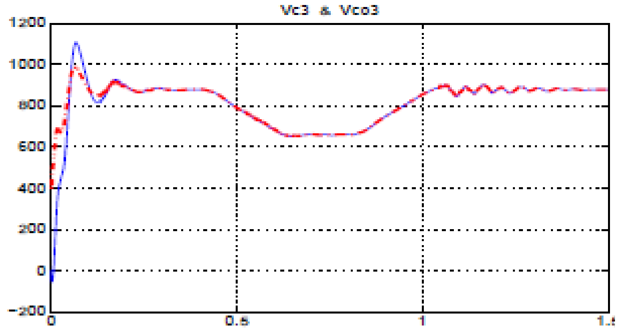

Fig. 6. Capacitor voltage *Vc3* and its estimation.

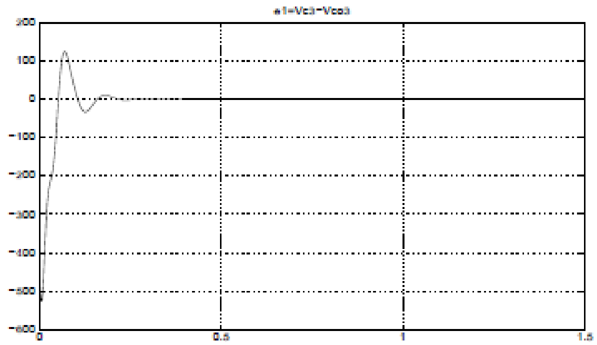

Fig. 7. Estimation error.

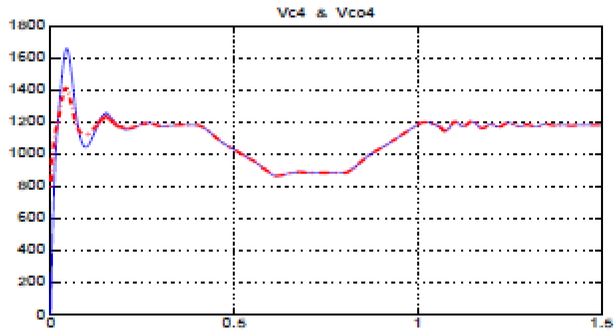

Fig. 8. Capacitor voltage *Vc4* and its estimation.

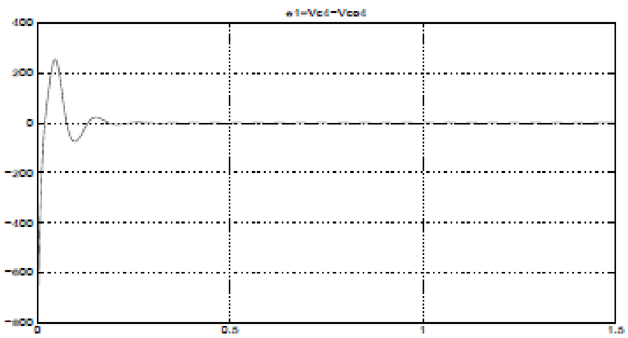

Fig. 9. Estimation error.

conditions to the observer for better initial transients, minimized the convergence time and increase the the performance of the observer when the states estimated are replaced in a control algorithm.

The current and its estimation are given in Fig. 10. From Figs. 10 and 11, we can see that the observer performs very well.

Finally, Fig. 12, represents the trajectory of the input *E*. In fact, in order to see the performance ofg the observer, a change in the value of the source voltage *E* is introduced as shown in Fig. 12.

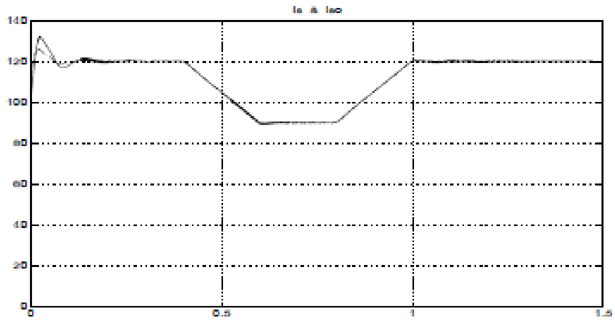

Fig. 10. The current *Is* and its estimation.

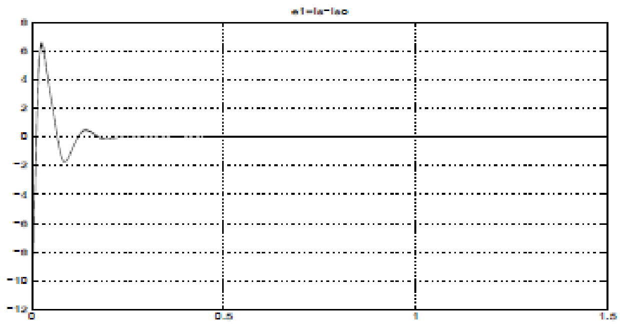

Fig. 11. Estimation error.

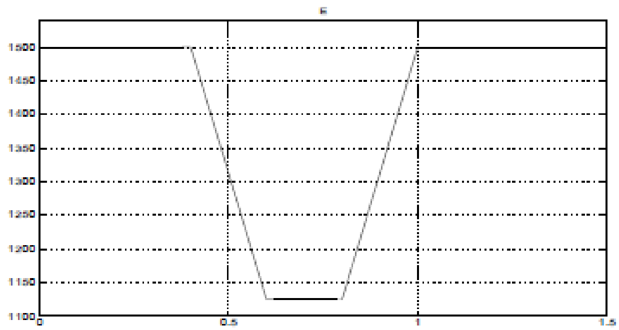

Fig. 12. Input trajectory *E*.

6. Interconnected Observer for Unknown Parameters

6.1 Observer with Unknown Input Voltage E

Now, consider a 2 cell chopper converter and assume that the voltage of the source *E* is constant and unknown. Following the same procedure as above, we can design an observer for the system

$$\sum_{2cell}:\begin{cases}\dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c\\ \dfrac{dv_{ck}}{dt} = \dfrac{1}{c_k}(S_{k+1} - S_k)\, i\\ \dfrac{dE}{dt} = 0\\ y = I\end{cases}$$

In order to estimate simultaneously the capacitor voltage *vc* and the voltage of the source *E*. The corresponding interconnected subsystem can be written as follows

$$\begin{cases}\dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c\\ \dfrac{dv_{ck}}{dt} = \dfrac{1}{c_k}(S_{k+1} - S_k)\, i\end{cases}$$

$$\begin{cases}\dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c\\ \dfrac{dE}{dt} = 0\end{cases}$$

Representing in a compact form, it follows that

$$\sum_1 : \begin{cases}\dot{X}_1 = A_1(u)X + B_1(u, E)\\ y = C_1 X_1\end{cases}$$

$$\sum_2 : \begin{cases}\dot{X}_2 = A_2(u)X + B_2(u, v_c)\\ y = C_2 X_2\end{cases}$$

Where $X_1 = (I, v_c)^T$, *and* $X_2 = (I, E)^T$

Are the state vectors of each subsystem $u = (S_2, -S_1)$

Is the input $B_1(u,E) = \dfrac{E}{L}S_2$, $B_2(u,v_c) = \dfrac{S_2 - S_1}{L}v_c$

$$A_1(u) = \begin{pmatrix} -\dfrac{R}{L} & -\dfrac{S_2 - S_1}{L}\\ \dfrac{S_2 - S_1}{L} & 0\end{pmatrix},$$

$$A_2(u) = \begin{pmatrix} -\dfrac{R}{L} & \dfrac{S_2}{L}\\ 0 & 0\end{pmatrix}$$

Then, an interconnected observer for the above interconnected system is given by

$$O_1 : \begin{cases}\dot{Z}_1 = A_1(u)Z_1 + B_1(u, \hat{E}) - P_1^{-1} C_1^T (y - \hat{y})\\ \dot{P}_1 = -\theta_1 P_1 - A_1^T(u)P_1 - P_1 A_1(u) + C_1^T C_1\end{cases}$$

$$O_2 : \begin{cases}\dot{Z}_2 = A_2(u)Z_2 + B_2(u, \hat{v}_c) - P_2^{-1} C_2^T (y - \hat{y})\\ \dot{P}_2 = -\theta_2 P_2 - A_2^T(u_1)P_2 - P_2 A_2(u) + C_2^T C_2\end{cases}$$

Where $Z_1 = \left(\hat{I}, \hat{v}_c\right)^T$, *and* $Z_2 = \left(\hat{I}, \hat{E}\right)^T$

Are the estimation states of each subsystem.

Now, we present some simulation results obtained by using the proposed observer. In order to illustrate the performance of the proposed observer, a 2-cell converter instantaneous model described by (2) is considered, where the capacitor voltage *vc* and the voltage of the source *E* are no measurable. The parameters considered for simulation of a 5 cells converter are used to perform simuations for the 2 cells converter.

In Fig. 13, we can see that the estimate capacitor voltage converges to the real variable while the estimation error is given in Fig. 14. Furthermore, from simulations we can see that the source E is well estimated using the proposed methodology as shown in figure 15, we show that the observer performs very well in the case of study when the change of 40% in the voltage source occurs (see figure 16 for the estimation error of the input voltage E).

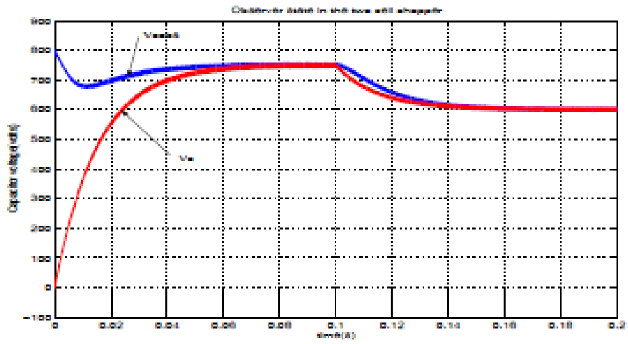

Fig. 13. Capacitor voltage *Vc* and its estimation.

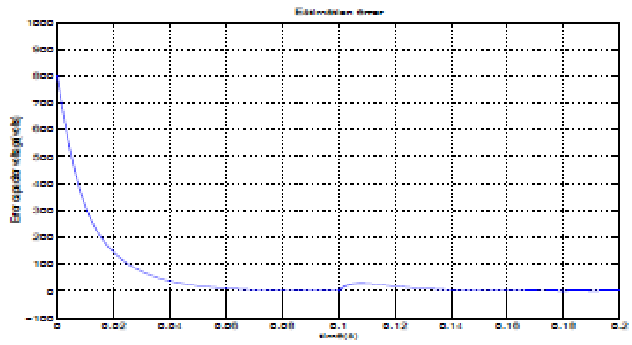

Fig. 14. Estimation error.

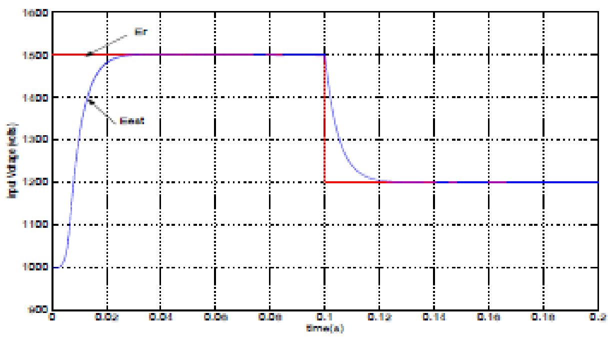

Fig. 15. Input *E* and its estimation.

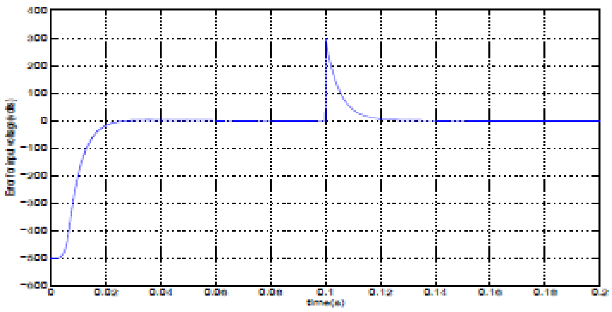

Fig. 16. Estimation error.

6.2 Observer for Estimating the Resistance R

Now, we are going to construct an interconnected observer in order to estimate the capacitor voltage *vc* and the resistance *R*, simultaneously, of 2 cell chopper converter. In this case, we can extend, without lost of generality, the results obtained above to the case where the matrices *Ai*, for $i = 1,\dots p$, are function of the input *u* and the output *y*, (for more details see H, De Leon).

Now, consider a 2-cell chopper converter described by

$$\sum_{2cell}: \begin{cases} \dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c \\ \dfrac{dv_{ck}}{dt} = \dfrac{1}{c_k}(S_{k+1} - S_k)\, i \\ \dfrac{dR}{dt} = 0 \\ y = I \end{cases}$$

where the resistance *R* is assumed constant and unknown, the measurable output is the current *I*. Since the observability space of this system is of dimension 2, and then the above system is partially observable.

However, it is possible to estimate the capacitor voltage and the resistance *R* from the measured current *I*.

For that, we will design an observer constituted by a set of interconnected observers in order to estimate the capacitor voltage *vc* and the resistance *R*, simultaneously.

Now, we extend the proposed methodology for which is possible to design an observer.

The mathematical model of 2 cell chopper can be rewritten in a set of interconnected state affine subsystems as follows:

$$\begin{cases} \dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c \\ \dfrac{dv_{ck}}{dt} = \dfrac{1}{c_k}(S_{k+1} - S_k)\, i \end{cases}$$

$$\begin{cases} \dfrac{dI}{dt} = -\dfrac{R}{L}I + \dfrac{E}{L}S_p - \dfrac{(s_2 - s_1)}{L}v_c \\ \dfrac{dR}{dt} = 0 \end{cases}$$

The above systems can be represented in an interconnected compact form as follows:

$$\sum_1: \begin{cases} \dot{X}_1 = A_1(u)X + B_1(u,R) \\ y = C_1 X_1 = I \end{cases}$$

$$\sum_2: \begin{cases} \dot{X}_2 = A_2(u)X + B_2(u,v_c) \\ y = C_2 X_2 = I \end{cases}$$

Where $X_1 = (I, v_c)^T$, *and* $X_2 = (I, R)^T$

Are the state vectors of each subsystem $u = (S_2, -S_1)$

Is the input, $Y = I$ is output of each subsystem and $C_1 = C_2 = (1 \quad 0)$

Furthermore, the interconnected terms are given by

$$B_1(u,R) = \frac{E}{L}S_2 - \frac{R}{L}I, \quad B_2(u,v_c) = \frac{E}{L}S_2 - \frac{S_2 - S_1}{L}v_c$$

$$A_1(u) = \begin{pmatrix} 0 & -\dfrac{S_2 - S_1}{L} \\ \dfrac{S_2 - S_1}{L} & 0 \end{pmatrix},$$

$$A_2(u) = \begin{pmatrix} 0 & -\dfrac{1}{L} \\ 0 & 0 \end{pmatrix}$$

Then, an observer for these interconnected systems is given by:

$$O_1: \begin{cases} \dot{Z}_1 = A_1(u)Z_1 + B_1(u, \hat{R}) - P_1^{-1} C_1^T (y - \hat{y}) \\ \dot{P}_1 = -\theta_1 P_1 - A_1^T(u)P_1 - P_1 A_1(u) + C_1^T C_1 \end{cases}$$

$$O_2: \begin{cases} \dot{Z}_2 = A_2(u)Z_2 + B_2(u, \hat{v}_c) - P_2^{-1} C_2^T (y - \hat{y}) \\ \dot{P}_2 = -\theta_2 P_2 - A_2^T(u_1)P_2 - P_2 A_2(u) + C_2^T C_2 \end{cases}$$

Where $Z_1 = \left(\hat{I}, \hat{v}_c\right)^T$, *and* $Z_2 = \left(\hat{I}, \hat{R}\right)^T$

The Figs. 17-20 show the performance of the proposed observer. We can see that the voltage is correctly well estimated and, in Fig. 17, we give the estimation of the resistance in Fig. 19, which converges to the actual value, satisfactorily and tacking into account the change of the resistance value up to 20%.

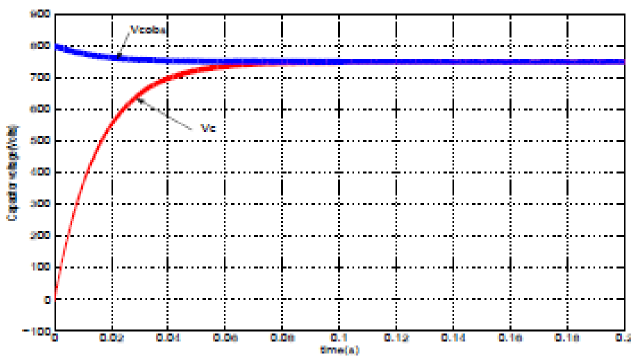

Fig. 17. Voltage estimation.

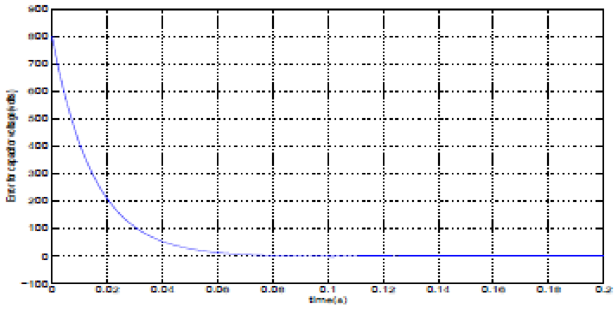

Fig. 18. Estimation error.

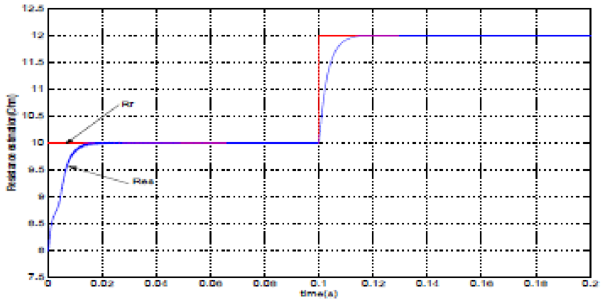

Fig. 19. *R* estimation.

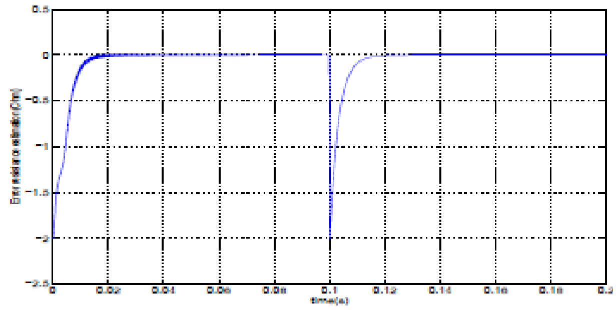

Fig. 20. Estimation error of *R*.

6.3 Experimental Results

In this section, we show some experimental results obtained by using the proposed interconnected observer. In order to illustrate the performance of this observer, where the estimates states converge to the real states, the instantaneous converter model of 5 cells (9) is used for the observer design, where the capacitor voltages have been considered unmeasurable.

The parameters of the model were chosen as follows:

f_d=16kHz, C=40μF, L=1mH, R=100Ω, E=120V.

Furthermore, to carry out the experimentation and show the efficiency of the proposed observer, we use a trajectory for the input voltage as given in Fig. 23.

Finally, the following initial conditions of the system and the observer were selected as follows:

For the system: $X_k = (I, v_{ck})^T=(0, 0)^T$ and for the observer: $Z_k = (\hat{i}, \hat{v}_{ck})$ are given as (1, 20), (1, 30), (1, 35) and (1,40) for k=1, …, 4.

The parameters θ_k, for k=1, …, 4; which are the design parameters used to control the rate of convergence of each observer, were chosen as follows: θ_1=30, θ_2=40, θ_3=50 and θ_4=60.

7. Benchmark Observation

The experimental setup realized based on the DS1103 dSPACE kit (Fig. 21) gives the global scheme of the experimental setup. This kit allows real time implementation of converter, it includes several functions such as analog/digital converters and digital signal filtering. In order to run the application we must write our algorithm in C language. Then, we use the RTW and RTI packages to compile and load the algorithm on processor. To visualize and adjust the control parameters in real time we use the software control-desk which allows conducting the process by the computer.

The multi-cells chopper power stage is based on the use of MOSFET. The pulse width-modulator (PWM) blocks are generated by FPGA card. The observer is first designed in Simulink/Matlab, then, the Real-Time Workshop is used to automatically generate optimized C code for real time applications. Afterward, the interface between Simulink/Matlab and the digital signal processor (DSP) (DS1103 of dSpace) allows the control algorithm to be run on the hardware.

The master bit I/O is used to generate the required 5 gate signals, and six analog-to-digital converters (ADCs) are used for the sensed line-currents, capacitors voltage, and output voltages. An optical interface board is also designed in order to isolate the entire DSP master bit I/O and ADCS. The block diagram of the experimental plant is given in Fig. 22.

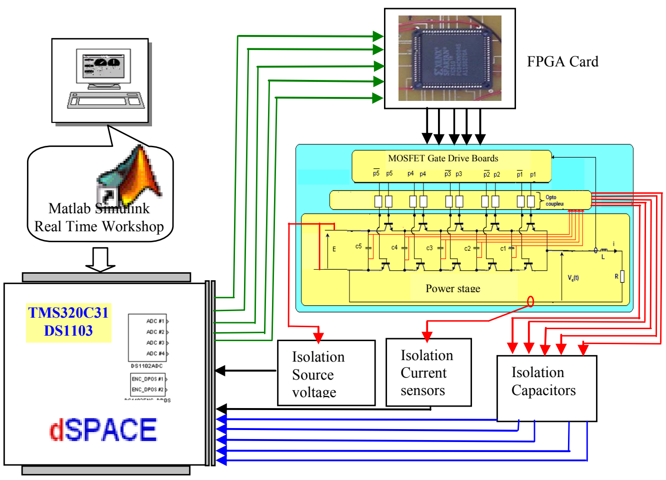

Fig. 21. General structure of the dSPACE observer.

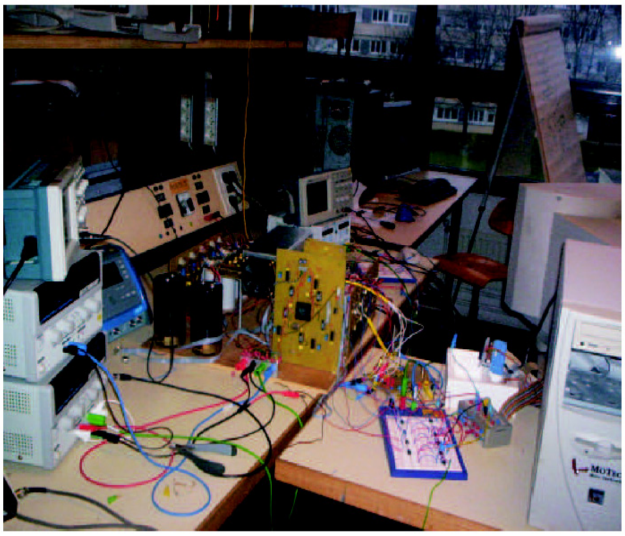

Fig. 22. Snapshot of the laboratory experimental setup.

8. Experimental Evaluation

The experimental results of Figs. 24-28 are obtained under the following test conditions: The sample time was chosen equal to 50 micro-seconds, and the data acquisition is close equal to 1 sec in this experimental evaluation. We assume that all parameter are known. In order to compare the real and estimated voltages 4 sensors were used, an optical interface was used in this case. Furthermore, to reduce the noise in the signals, a low pass filter was required. In the Figs. 24-27, we can see the convergence of the estimates and real voltage given by the observer to the real variables, this highlights the well fader performance of the proposed observation scheme. Form these plots, we can see that substantial transient of the voltages estimated, it is due to the error in the initial conditions. However, these transients can be reduced choosing suitable initial conditions of the observer. In this experiment, the initial conditions were chosen far of them of the converter to show the performance of the observer. The output current i is given in Fig. 28. The input voltage E is given in Fig. 23. Note that all experimental results are obtained buy using a second order filter.

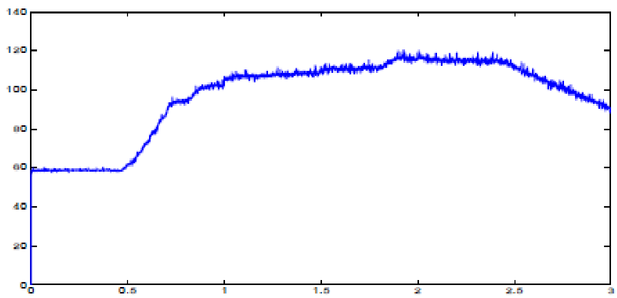

Fig. 23. The input voltage E.

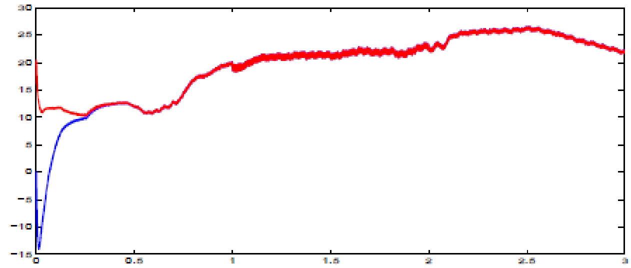

Fig. 24. Capacitor voltage $Vc1$ measured and its estimated.

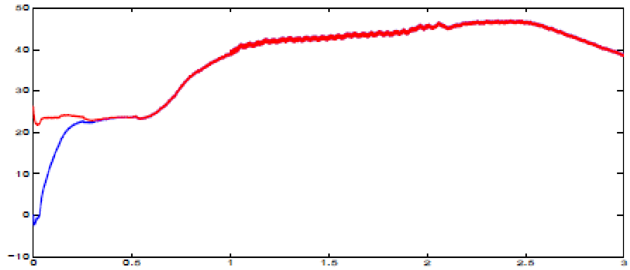

Fig. 25. Capacitor voltage $Vc2$ measured and its estimated.

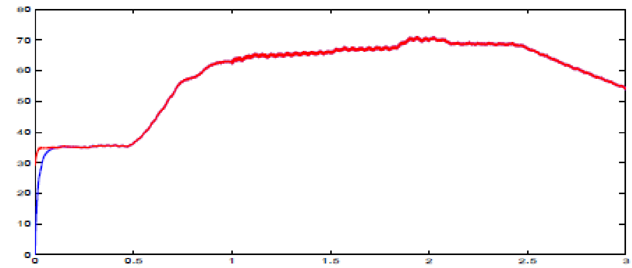

Fig. 26. Capacitor voltage $Vc3$ measured and its estimated.

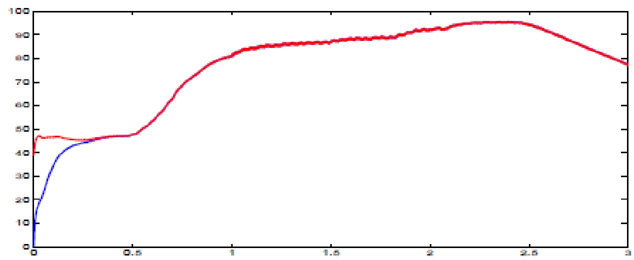

Fig. 27. Capacitor voltage $Vc4$ measured and its estimated.

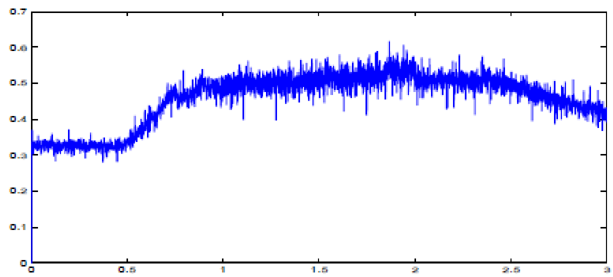

Fig. 28. The output current load.

9. Conclusion

In this paper, an interconnected observer has been presented. Sufficient condition are given in order to prove its exponential convergence. Furthermore, using an instantaneous model of a 5-cell chopper, an interconnected observer designs have been presented. The practical interest of such observers has been was illustrated by means of simulation results. Using only the instantaneous measurement of the current, the capacitor voltage has been well estimated. Furthermore, the proposed interconnected observer has been applied to a 2-cell chopper, where some parameter has been assumed constant and unknown.

In the first case, the capacitor voltage and the source E, which has been considered constant and unknown, have been estimated satisfactorily. Finally, an extension of this work have been done for a class of nonlinear systems state affine, where de matrices are function of the input and the output, has been considered as well, when in this case the resistance was assumed constant and unknown. Simulation results have been given illustrating the performance of the proposed observer. To show the validity of our approach, experimental based a DSP results are presented.

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Appendix: Some Mathematical Preliminaries

Proof. In order to prove the convergence of the observer (8), first we consider the dynamics of the subsystem (3), for which an observer of the form (6) can be designed. Then, defining the estimation error $\varepsilon_k = Z_k - X_k$ whose dynamics is given by

$$\dot{\varepsilon}_k = \{A(u_k) - P_k^{-1} C_k^T C_k\}\varepsilon_k + \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)$$

where $\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k) = B_k(\bar{u}_k, \bar{Z}_k) - B_k(\bar{u}_k, \bar{X}_k)$, for k=1, …, p-1;

From assumption 1 and lemma 1 (see appendix), we can define $V = \sum_{l=1}^{p-1} V_k$ as a lyapunov function for the interconnected system (7), where $V(\varepsilon_k) = \varepsilon_k^T P_k \varepsilon_k$ is a Lyapunov function for subsystem (3). It is clear that these functions are well defined because the matrices P_k are non-singular.

Taking the time derivative of $V(\varepsilon_k)$, it follows that

$$\dot{V}(\varepsilon_k) \le -\theta_k V(\varepsilon_k) + \varepsilon_j^T P_k \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k) \text{ for } k = 1, \dots, p-1$$

Now, adding and subtracting the term $\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)^T P_k \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)$, we have

$$\dot{V}(\varepsilon_k) \le -\theta_k V(\varepsilon_k) + 2\varepsilon_k^T P_k \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k) \pm \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)^T P_k \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)$$

Next, regrouping the appropriate terms

$$\begin{aligned}\dot{V}(\varepsilon_k) \quad \le \quad & -(\theta_k - 1)\|\varepsilon_k\|^2 P_k \\ & -\|\varepsilon_k\|^2 P_k + 2\varepsilon_k^T P_k \Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k) - \|\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)\|^2 P_k \\ & \|\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)\|^2 P_k\end{aligned}$$

It follows that

$$\dot{V}(\varepsilon_k) \le -(\theta_k - 1)\|\varepsilon_k\|^2 P_k + \|\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)\|^2 P_k$$

Now, from assumption 2, $B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)$ is Lipschitz, it follows that

$$\|\Delta B_k(\bar{u}_k, \bar{X}_k, \bar{Z}_k)\|^2 P_k < \sum_{l=1, l\neq k}^{p-1} \lambda_l \|\varepsilon_l\|^2 p_k$$

we get then,

$$\dot{V}(\varepsilon_k) \le -(\theta_k - 1)\|\varepsilon_k\|^2 P_k + \lambda_l \|\varepsilon_l\|^2 P_k$$

the time derivative of V is given by

$$\dot{V}(\varepsilon) = \sum_{k=1}^{p-1} \dot{V}(\varepsilon_k)$$

$$\dot{V}(\varepsilon) \le \sum_{k=1}^{p-1} \left\{-(\theta_k - 1)\|\varepsilon_k\|^2 P_k + \sum_{l=1, l\neq k}^{p} \lambda_l \|\varepsilon_l\|^2 P_k\right\}$$

Using the lemma on equivalence of norms, i.e. it exists a positive constant μ_l such that

$$\|\varepsilon_l\|^2 P_k \le \mu_l \|\varepsilon_l\|^2 P_l, \quad \forall\, l = 1, \dots, p-1$$

Then, it follows that

$$\dot{V}(\varepsilon) \le \sum_{k=1}^{p-1} \left\{-(\theta_k - 1)\|\varepsilon_k\|^2 p_k + \sum_{l=1, l\neq k}^{p-1} \lambda_l \mu_l \|\varepsilon_l\|^2 p_k\right\}$$

Or

$$\dot{V}(\varepsilon) \le \sum_{k=1}^{p-1} -\{(\theta_k - 1) - (p-1)\lambda_l \mu_l\}\|\varepsilon_j\|^2 P_k$$

Finally, we have $V(\varepsilon) \le V(\varepsilon(t_0))e^{-\gamma(t-t0)}$, for $\gamma = \min(\gamma_1, \dots,$

γ_{p-1}) where $\gamma_k=(\theta_k-1)-(p-1)\lambda_k\mu_k$. Taking $\varepsilon=col(\varepsilon_1, \dots, \varepsilon_{p-1})$, it is easy to see that

$$\|\varepsilon(t)\| \leq K \|\varepsilon(t_0)\| e^{-\gamma(t-t_0)}$$

This ends the proof.

Now, we introduce some definitions related with the inputs applied to the system. Consider a state-affine controlled system of the following form

$$\begin{cases} \dot{x} = A(v)\ x + B(v) \\ y = C\ x \end{cases}$$

where $x \in R^n;\ v \in R^m;\ y \in R^p$ with $A:\ R^m \to M(n,m);\ B:\ R^m \to M(n,l)$ continuous, and $C \in M(p,n)$, where $M(k,l)$ denotes the space of k x l matrices with coefficients in R; k (resp.l) is the number of rows (resp. columns).

Notation Let $\Phi_v(\tau,t)$ denotes the transition matrix of:

$$\frac{d}{dt}\Phi_v(\tau, t) = A(v(\tau))\,\Phi_v(\tau, t)$$
$$\Phi_v(t,t) = I$$

with the classical relation:

$$\Phi_v(t_1, t_2)\Phi_v(t_2, t_3) = \Phi_v(t_1, t_3)$$

We then define:

- The Observability Grammian:

$$\Gamma(t,T,v) = \int_t^{t+T} \Phi_v^T(\tau, t)\, C^T\, C\, \Phi_v(\tau, t)\, d\tau$$

- The Universality index :

$$\gamma(t, T, v) = \min(\lambda_i(\Gamma(t, T, v)))$$

where the $\lambda_i(M)$ stand for the eigenvalues of a given matrix M.

The input functions are assumed to be measurable and such that A(v) is bounded on the set of admissible inputs of $\mathbf{R}^+$. We recall below some required results of input functions ensuring the existence of an observer for (3).

Definition 1 (Regular Persistence). A measurable bounded input v is said to be regularly persistent for the state-affine system (3) if there exist $T > 0$; $\alpha > 0$ and $t_0 > 0$ such that $\gamma(t, T, v) > \alpha$ for every $t \geq t_0$.

Now, a further result based on regular persistence is introduced.

Lemma 1 Assume that the input u_k is regularly persistent for system (2) and consider the following Lyapunov differential equation:

$$\dot{P}_k = -\theta_k P_k - A^T(u_k)P_k - P_k A(u_k) + C_k^T C_k$$

with $P_k(0)>0$. Then, $\exists\theta_{k0}>0$ such that for any symmetric positive definite matrix $P_k(0)$,

$$\exists\theta_k \geq \theta_{k0},\quad \exists\alpha_k,\ \beta_k > 0,\ t_0 > 0 :\ \forall t > t_0$$
$$\alpha_k I < P_k(t) < \beta_k I$$

where I is the identity matrix.