A Port-Hamiltonian Approach to Control DC-DC Power Converters

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Abstract: Port-Hamiltonian system is a modeling and control methodology developed in recent decades. It is focused on energy transfer among different parts of a system and between systems. Power converters on the other hand are devices that process the electrical energy at its input to deliver energy with the required characteristic at its output. Hence, a Port-Hamiltonian model is especially attractive for control of power converters. Based on previous published results, in this paper, a Port-Hamiltonian approach is proposed for the control of DC-DC power converters. A particular characteristic of the controller here proposed is that a time variable inductor current is employed. As a result a faster and lower overshoot closed loop response is obtained for both the start-up condition and the load disturbance.

Keywords: Port-Hamiltonian, Energy, Power, Power electronics, Power converters, Energy shaping.

1. Introduction

Energy is a fundamental and common concept of different domains that can be used as a kind of communication language between systems. Energy based control has its origins on mechanical systems. Euler-Lagrange and Hamiltonian dynamics methodologies allow to obtain a dynamical model based on the energy stored on the system. In recent decades, a new methodology has been developed. The Port-Hamiltonian technique is a power port based control tehcnique, which adopted the ideas from Hamiltonian mechanics and the Bond-Graph port description [29]. The Port-Hamiltonian modeling represents the systems as interconnection ports, where the product of the port variables is the power, that is the rate of change of energy. Power converters on the other hand can be seen as energy processors. They transform the electric energy at its input port to deliver energy at its output port with the characteristics required by the load. Hence, Port-Hamiltonian approach seems to be especially suitable for modeling and control of power converters.

The common scheme to control power converters is based on the direct measurement of the output voltage and inductors currents. Many results have been reported, they are generally based on the classic control, focusing on a signal analysis. Other approaches to control power converters are based on the sliding mode control technique [16, 28, 29], in which the discontinuous nature of converters is matched with the technique. The evolution of power converters depends on the renewable energies, and in such way the controllers need to evolve and some new techniques must emerge [27]. In recent years an energy based viewpoint is starting to be adopted in the control of power converters. The energy based viewpoint could benefit from the evolution of the control of power electronic converters, because the energy is the fundamental concept on power electronics.

The first applications of the Port-Hamiltonian control technique were developed for mechanical systems [1, 10, 17]. Over the years, the Port-Hamiltonian approach has been applied to different kind of systems. For example, it has been applied to robotics [9, 26, 35], mechanical systems [1, 5, 30], power electronic converters [4, 8, 23, 25, 31, 32, 33, 34], electrical motors [3, 4, 12] among many others. The Port-Hamiltonian approach is a relatively new approach to control systems, some controllers developed using this technique have shown excellent performance. As the technique is relative recent there is a lot of work under development. Application of the Port-Hamiltonian approach to control power converters is somewhat more difficult than for mechanical systems. In most mechanical systems, there is no dissipation or it can be neglected. On the other hand, in power electronic converters the system demands energy all the time unless they are shut down.

Application of the Port-Hamiltonian approach to power electronic converters motivated the development of several methodologies. For example, control by energy balance [2, 10, 19],

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control by interconnection [18, 19, 20] and interconnection and damping assignment passivity based control (IDA-PBC) [12, 21, 29].

Developing a model for power converters suitable for the Port-Hamiltonian control was a challenge because the discontinuous nature of power converters. However, a suitable model that maintains the Port-Hamiltonian structure was proposed in [8, 33].

Most of the energy based control strategies proposed for power electronics use the so called energy shaping control [2, 15, 18, 19, 20, 25, 32], which sounds as a natural strategy to apply on power electronic converters since those devices regulate the energy transfer from the input to the output.

For example, a control that reduces the ripple using the Port-Hamiltonian viewpoint is presented on [33]. There are some works that regulate the output voltage of DC-DC converter, see [25, 32]. Port-Hamiltonian control have also been applied to DC-AC converters see [4, 23]. Port-Hamiltonian has been combined with other techniques. For example, in [22] a PI regulator is added. In [34] some varying constraints are overcome by energy shaping control.

Of particular interest for the results presented in this paper is the controller presented in [32]. In this paper, a Port-Hamiltonian approach with an energy shaping control strategy is employed. It is an interesting result; however, the response is too slow to be practical. One cause of the slow response is that inductor and capacitor values chosen by the authors are too big. This is easy to solve and could alleviate part of the problem. Nevertheless, we consider the controller could be further improved with some modification proposed in this paper. Such modification consists in making time variable references that are usually constants. Introducing these changes yields a significant improvement in closed loop response. It is much faster in the start-up condition and under load disturbance. For fast converters, a lower overshoot is achieved.

The rest of paper is organized as follows; In Section 2 the controller proposed in [32] is revisited. The modeling and control strategy followed by the authors is analyzed. In Section 3 the proposal to enhance the performance is presented. In Section 4 simulation results to evaluate the controller performance are shown. For comparison, the controller proposed in [32] is also simulated. In Section 5 it is discussed how could be possible to extend the Port-Hamiltonian approach to other kind of power electronic converters to enhance their performance. Finally, in Section 6 some conclusions are presented.

2. Previous results in Port-Hamiltonian approach to control of DC-DC power converters

In this Section, some previously published results that use the P-H approach for modeling and control of power converters are summarized.

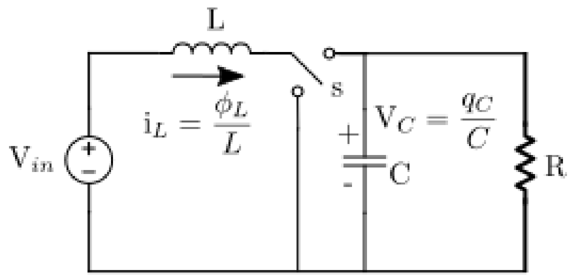

Figure 1. Boost converter

The general structure of a Port-Hamiltonian system is

$$\dot{x} = \left[J - \bar{R} \right] \frac{\partial H(x)}{\partial x} + gu \tag{1a}$$

$$y = g^T \frac{\partial H(x)}{\partial x}, \tag{1b}$$

where x is the system vector state, J is called the interconnection matrix, $\bar{R}$ is called the dissipation matrix, and g is the input matrix. Matrix J is skew symmetric and R is positive semidefinite. $H(x)$ is the Hamiltonian of the system and is defined by each system energy storage and u is the input power port. The Port-Hamiltonian technique can be used for modeling and control linear and nonlinear systems. In many cases nonlinearities arise due to nonlinear elements of J, $\bar{R}$ and g.

For the case of power converters there are some works that develop models using the Port-Hamiltonian approach [4, 6, 8, 12, 13, 29].

The general form of a Port-Hamiltonian model of power converters is

$$\dot{x} = \left[J(s,x) - \bar{R}(s,x)\right]\frac{\partial H(x)}{\partial x} + g(s)u \tag{2a}$$

$$y = g^T(s,x)\frac{\partial H(x)}{\partial x}, \tag{2b}$$

where s is the switch duty cycle which is the control element, u is the input of the power port, which in this particular case is the input voltage V_{in}. As can be observed, in the case of power converters, matrices J, $\bar{R}$ and g could depend on s.

In [32] the particular case of boost converter shown in Figure 1 is developed. The obtained model is in the form of (2) with

$$x = \begin{bmatrix} \phi_L \\ q_C \end{bmatrix} \tag{3a}$$

$$H = \frac{\phi_L^2}{2L} + \frac{q_C^2}{2C} \tag{3b}$$

$$J = \begin{bmatrix} 0 & -s \\ s & 0 \end{bmatrix} \tag{3c}$$

$$\bar{R} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{R} \end{bmatrix} \tag{3d}$$

$$g = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \tag{3e}$$

where the system state is given by ϕ_L, the magnetic flux on the inductor and q_c, the charge on the capacitor. The Hamiltonian of the system *(H)* is the energy stored in inductor and capacitor. L is the inductance value, C is the capacitance value, R is the resistor value and s is the control (switch duty cycle).

In practical setting, inductor current and capacitor voltage are measured. These variables are related with inductor magnetic flux and capacitor electric charge by

$$x = \begin{bmatrix} \phi_L \\ q_C \end{bmatrix} = \begin{bmatrix} Li_L \\ CV_C \end{bmatrix}, \tag{4}$$

where i_L is the inductor current and V_C is the capacitor voltage.

The control goal of the boost converter is to regulate the output voltage V_C to a desired voltage V_{Cd}, that is to achieve $V_C \rightarrow V_{Cd}$. In a Port-Hamiltonian approach, this control goal is more convenient expressed as $q_C \rightarrow q_{Cd} = CV_{Cd}$. When $V_C \equiv V_{Cd}$ there is an equilibrium point. Substituting (3) in (2) and solving the resulting equation with derivative equal to zero for i_L, assuming $V_C \equiv V_{Cd}$ and (4), it is possible to find the equilibrium point

$$i_L \equiv i_{Ld} = \frac{V_{Cd}^2}{RV_{in}}, \tag{5}$$

or

$$\phi_L \equiv Li_{Ld} = L\frac{V_{Cd}^2}{RV_{in}}, \tag{6}$$

where V_{in} is the input voltage supplied to the converter. Hence, it can be said that the control goal of the boost converter is to select the duty cycle s to make the equilibrium point

$$\left(\phi_{Ld}, q_{Cd}\right) = \left(L\frac{V_{Cd}^2}{RV_{in}}, CV_{Cd}\right), \tag{7}$$

asymptotically stable.

The usual Port-Hamiltonian approach to control is to make the closed loop system behaves as

$$\dot{x} = \left[J_d(s,x) - R_d(x)\right]\frac{\partial H_d(x)}{\partial x}, \tag{8}$$

where

$$J_d = J + J_a \tag{9a}$$

$$R_d = R + R_a \tag{9b}$$

Matrices J_a, R_a and function H_d are to be designed to achieve the desired closed loop behavior of the system. Note that to keep the system structure, J_d, R_d must be skew symmetric and positive definite respectively. The function H_d has to be energy related as well.

In [32] J_a, R_a and H_d are selected as

$$J_a = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{10a}$$

$$R_a = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix} \tag{10b}$$

$$H_d = \frac{\left(\phi_L - \phi_{Ld}\right)^2}{2L} + \frac{\left(q_C - q_{Cd}\right)^2}{2C}, \tag{10c}$$

By making the choice given by an asymptotically stable equilibrium point we obtain $(\phi_L, q_C) = (\phi_{Ld}, q_{Cd})$, that is

$$\phi_L \to \phi_{Ld}, q_C \to q_{Cd}, \tag{11}$$

is achieved.

To make the system (2, 3) behaves in closed loop like (10) and hence, (11) be accomplished a procedure to select the control *s* and parameters for matrices J_a and R_a is necessary. By relating the interconnection and damping structures of open and closed loop systems, in [10, 19] it is found that this can be achieved solving the partial differential equation

$$\left[J_d(s,x) - R_d(x)\right]\frac{\partial H_d(x)}{\partial x_d} = -\left[J_a - R_a\right]\frac{\partial H(x)}{\partial x} + gu \tag{12}$$

Using (3), (4) and (10) in (12), and solving for *s* it is obtained that both equalities

$$s = \frac{r_1(i_L - i_{Ld}) + V_{in}}{V_{Cd}} \tag{13a}$$

$$s = \frac{V_{Cd}}{Ri_{Ld}} - \frac{r_2(V_C - V_{Cd})}{i_{Ld}} \tag{13b}$$

must be accomplished.

Any of the equations (13a) or (13b) could be used as a control law for the boost converter, however to be completely determined it is necessary to propose r_1 and r_2.

To find appropriate values for r_1 and r_2 the following considerations can be taken into account:

- Matrix R_d must be positive definite, that is

$$r_1 > 0 \tag{14a}$$

$$\frac{1}{R} + r_2 > 0 \tag{14b}$$

must be hold.

- The duty cycle *s* must satisfy

$$0 \le s \le 1 \tag{15}$$

Substituting (13a) in (15) yields

$$0 \le \frac{r_1(i_L - i_{Ld}) + V_{in}}{V_{Cd}} \le 1 \tag{16}$$

solving (16) for r_1 results

$$0 \le r_1 \le \frac{V_{Cd} - V_{in}}{i_L - i_{Ld}} \tag{17}$$

Substituting (13b) in (15) yields

$$0 \le \frac{V_{Cd}}{Ri_{Ld}} - \frac{r_2(V_C - V_{Cd})}{i_{Ld}} \le 1 \tag{18}$$

solving (18) for r_2 results

$$\frac{V_{Cd}}{R(V_c - V_{Cd})} \le r_2 \le \frac{V_{Cd}}{R(V_c - V_{Cd})} - \frac{1}{(V_c - V_{Cd})} \tag{19}$$

Summing up, choosing r_1 and r_2 within ranges (17) and (19) and *s* according to (13a) or (13b) the equilibrium (ϕ_{Ld}, q_{Cd}) is asymptotically stable. That means that the goal given by (7) is achieved. Generally, expression (13a) is chosen for the duty cycle *s* due to it is easier to implement than (13b). Note that to implement (13a) a choice for r_1 and references for V_{Cd} and i_{Ld} are necessary voltage. V_{Cd} is a design data and generally in papers that use the Port-Hamiltonian approach i_{Ld} is set according to (5).

3. The proposed approach

In this section, the proposed approach is described. Based on previous results, the same expression for the duty cycle given by (13a) is used. However, two major modifications are made: the expression for the inductor current reference i_{Ld} and the selection of parameter r_1.

As a consequence of energy conservation, given some time, in any system and particularly in power converters input power and output power are approximately equal. That is

$$P_I \cong P_0, \tag{20}$$

where P_I is the input power and P_0 is the output power.

In the boost converter

$$P_I = V_{in} i_L \qquad (21a)$$

$$P_0 = V_C i_0 , \qquad (21b)$$

where i_0 is the output current. From (20) and (21a) it can be written

$$i_L \cong \frac{V_C i_0}{V_{in}} \qquad (22)$$

From previous considerations, it is reasonable to take the right side of (22) as a reference for the inductor current. That is

$$i_{Ld} = \frac{V_C i_0}{V_{in}} \qquad (23)$$

It must be pointed out that unlike [32] the reference given by (23) is time variable because V_c and i_0 are time dependent.

Let us now focus on parameter r_1 selection. As it has been shown r_1 must be within the range given by (17). It should be mentioned that the bigger r_1 the faster system trajectory converges to the equilibrium point. Hence, instead of using a conservative value for r_1 like in [32] it could be proposed the right side of range (17) for r_1 However, as the expression for r_1 is part of the controller expression it is convenient to keep r_1 simple.

To this end, the use of the minimum value of the range (17) is proposed. Such minimum value happens when . That leads to propose

$$r_1 = \frac{V_{Cd} - V_{in}}{i_{Ld}} \qquad (24)$$

Note that unlike [32], r_1 is also time variable because i_{Ld} and V_c are time dependent.

4. Simulation results

Simulations of the boost converter controlled by the proposed approach are presented in this section. For comparison, simulations of the approach described in [32] are also presented.

Figures 2 - 4 show the results obtained with the controller proposed (expressions (13a) (23) (24)) and the controller proposed in [32]. The converter parameters used to obtain the results are the same used in [32] and are presented on Table 1.

Table 1. Boost converter parameters to obtain Figures 2 - 4

Parameter	Value
V_{in}	20V
L	30mH
C	50μF
R	30Ω
V_d	40V

In [32], values for r_1 and i_{Ld} are the constants $r_1 = 0.5$ and $i_{Ld} = 2.223$ while here it is proposed to use time variable functions given by (23) and (24). To evaluate the performance under load disturbance, at $t = 0.025$ the load is suddenly change from 30Ω to 60Ω.

Figure 2 presents the output voltages of both approaches. It can be observed from this figure that the controller here proposed has a slightly faster response.

On Figure 3 the comparison between the currents is presented. It can be observed that the proposed controller has a faster response to reach the desired current.

On Figure 4 the control signal is shown. Note that the proposed controller has a wide range of variation of the control signal, that is the reason the converter response is faster. On the contrary, the control signal of the Tian et. al approach has smooth variations causing a slower response.

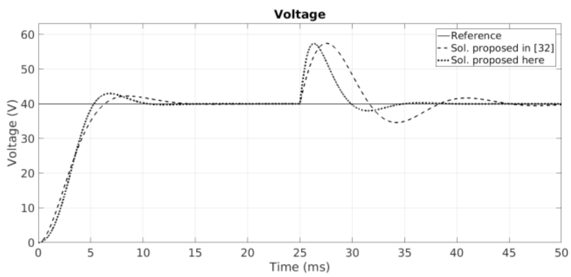

Figure 2. Voltage comparison

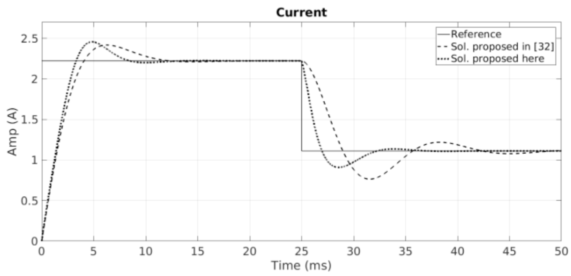

Figure 3. Current comparison

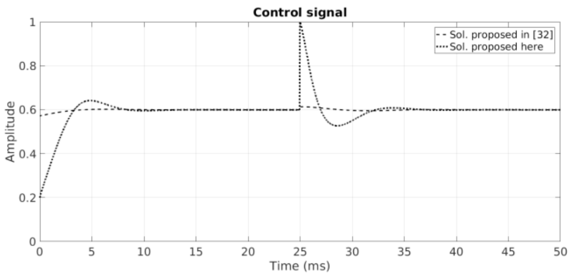

Figure 4. Control signal comparison

It is important to point out that parameters of Table 1 used in [32] are considered too big in power electronics practice. This parameters yield a converter with a too slow response for any controller. To design fast power converters, engineers look for the minimum values for inductors and capacitors that guarantee certain pre-specified maximum of voltage and current ripple. There are known expressions to calculate these values for DC-DC converters [7, 14, 24]. For example, if the maximum inductor current ripple is 900*mA* and the maximum output voltage ripple is 500*mV* parameters listed in Table 2 are obtained. These parameters lead to a boost converter with a significant faster and oscillatory response than that proposed in [32].

Table 2. Boost converter parameters to obtain Figures 5 - 7

Parameter	Value
V_{in}	20V
L	250µH
C	30µF
R	30Ω
V_d	40V

To evaluate the performance of the proposed controller in a more practical situation it was simulated with the parameters listed in Table 2. The results obtained are shown in Figures 5 - 7. For comparison, the performance obtained with constant values for r_1 and i_{Ld} are also shown. Again, to test the controller a load disturbance is introduced in $t = 3ms$.

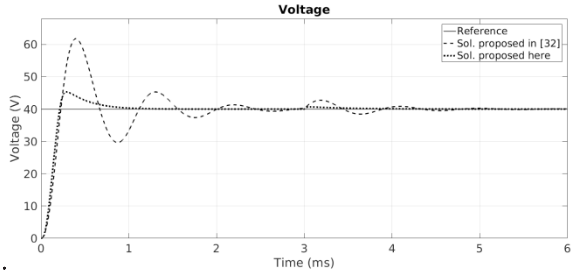

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Figure 5. Voltage comparison

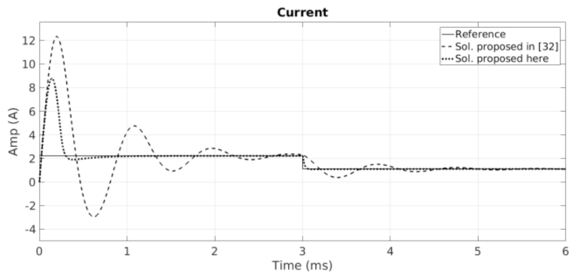

Figure 6. Current comparison

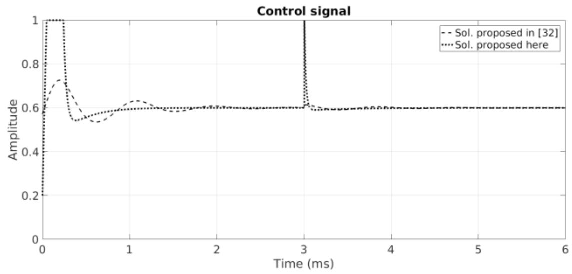

Figure 7. Control signal comparison

On Figure 5 the voltage response using parameters of Table 2 are shown. Note that in this case the settling time is reduced considerably. The proposed controller has a 5*V* overshoot compared to the 21*V* overshoot generated with the controller proposed in [32]. On the load disturbance presented at 3*ms* the proposed controller offers a lower overshoot.

Figure 6 shows the comparison of the currents. Note that in both cases the current reaches the desired value, but there are some differences between both controllers. The first difference is at startup where it can be observed that the current overshoot of the proposed controller is lower than that of the controller proposed in [32] by a difference of 4*A*. The proposed controller has almost no overshoot. It is also important to note that the settling time to reach the reference is almost the same for both controllers.

On Figure 7 the control signal is presented. It can be seen from this Figure that at startup both control signals have a wide variation before reaching the steady state. The load change on 3*ms* the control signal of the proposed controller has a peak of 0.75 in amplitude, this allows to regulate the voltage accurately and without too much overshoot.

From the results of this section it can be seen that the converter parameters are important to the transient response. Particularly the parameters of Table 1 are too big for a practical power converter and cause a slow response no matter what controller is employed. On the other hand, the parameters of Table 2 are more realistic and also offer a faster transient response as it was observed on Figures 5 - 7. For fast converters like this, the controller design plays an important part on the overall converter performance.

5. Application to other converters

Till this section results have been developed for the boost converter. However, application to other DC-DC converters is straightforward because ideas that lead to the controller expression (13a, 23, 24) can be applied almost verbatim to other DC-DC converters. Of course, matrices J, R and g change for different converters.

The power electronics converters evolve according to the technological requirements, in recent years the renewable energies are the ones demanding such upgrades. So, the control techniques applied need to evolve among the converters, that is the reason that different methodologies have been applied such as sliding mode control [16, 28, 29], among many other new variants [27] that come to solve emerging problems.

Application to different kind of converters is more complicated. However, for some converters (and other systems) passivity based controllers has been proposed (see [1, 3, 4, 8, 11, 12, 29, 30, 31, 33]). These controllers could be modified to use the Port-Hamiltonian approach like it is done in [32]. If any of these controllers require references the relation between input and output power could be used like it is done in this paper. Details of how to carry out this depicted procedure are different for every type of converter and will be developed in future works.

6. Conclusions

Some modifications to a research dealing with an energy-based controller are proposed in this paper. The proposed modifications make constant reference become time functions, particularly the reference for the inductor current. Such modifications result in a significantly faster and lower overshoot response in the converter start-up and under load disturbances as well.

It is important to point out that for controller evaluation, practical parameters should be used. A practical converter is usually fast and oscillatory. Under these circumstances performance differences among controllers are better appreciated. Some insights about how to apply the ideas behind the proposed controller to other kind of power converters have been given.

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