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Adaptive Passivity-based sliding mode control of a boost converter with parasitic parameters

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***Abstract*—This paper deals with robust control of boost converter with parasitic parameters. The effect of such parameters in passivity-based control law is investigated. The main objective of this work is designing a robust controller to annihilate the effect of these parameters. An Adaptive passivity-based sliding mode control is proposed for eliminating steady state error and improving the robustness of the control against variation of the DC source. The efficiency of the approach is proved in the simulated control of a Matlab/Simulink simscape model of a boost converter.**

I. Introduction

The control of power converters is an active field of research. This topic encounters some recent and challenging constraints. However, the energy management in industrial plants and even in domestic environments becomes the goal of an important number of scientists. On the other side, power converters need to be more efficient and the control of such components must have the main subject optimizing energy consumption adding to the classical required performance such as minimum response time and good robustness.

Electric energy is the most solicited energy nowadays. However, most of electrical applications need a wide range of DC and AC values of voltage. Power converters are components which provide various output voltages. DC/DC converters are used in applications such as cellphones, electronic processor cards, robotics, hybrid vehicles, etc. The topologies of such power converters are varied. One can find the configurations: buck, boost, buck-boost, sepic, cùk, etc. From the analysis point of view the performance of these converters depend on the type of applications [3]. These different structures lead to models with different complexity.

In this paper we treat the problem of parasitic parameters of a boost converter. The effect of these parameters in control law is investigated. The choice of passivity-based control (PBC) is essentially justified by the modeling strategy that we adopted which is energy based [5]. The principle of PBC is stabilizing systems by passivation with a storage energy function. This latter has a minimum at the desired equilibrium point. To ensure steady state error and robustness of the controller, we enriched the control law by a sliding manifold and an adaptive feedback. Section 2 outlines energetic modeling of the boost converter. Section 3 is devoted to our approach of control. Finally, section 4 concludes the paper.

II. Modeling the boost converter

A. Introduction

Modeling and analysis of boost converters as a DC/DC topology which gives an output voltage greater than the input one is a former issue in power electronics field. Most important modeling techniques are: sampled data models, switched state-space models and state-space averaged models. Sampled data models are suited for digital control implementation. Averaging techniques are most popular and frequently used by industrial to design and implement such converters. These techniques are applied directly on the converter scheme by replacing switching elements by their equivalent circuit. So that transistors, thyristors and diodes are replaced with voltage and current sources to obtain a time invariant circuit topology [1], [2], [3]. These manipulations are performed on circuit diagram instead of on its equations which gives a more physical interpretation to the model [1]. Nonlinear switches can be linearized leading to small signal AC models. Parasitic resistances of inductance, capacitor and switching elements can be considered in such model analysis to improve the accuracy of the converter model [4]. Circuit averaging technique can be applied to pulse width modulated boost converters with both continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM). State-space averaged models are generally nonlinear. As a first intuitive advantage is the possibility of applying nonlinear robust control techniques. Thereafter, our focus will be on energetic types of these models.

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B. Energetic approach for modeling

Energetic models reflects energetic behavior of the system during all the operating modes. Most important approaches are Euler-Lagrange and Hamiltonian models. Euler-Lagrange models are suited for mechanical systems such as robotics. The differential equation is as follows [5]

$$\frac{d}{dt}\frac{\partial \mathcal{L}}{\partial \dot{q}}(q,\dot{q}) - \frac{\partial \mathcal{L}}{\partial q}(q,\dot{q}) + \frac{\partial \mathcal{F}}{\partial \dot{q}}(\dot{q}) = \mathcal{M}u + Q_\zeta \qquad (1)$$

$$\mathcal{L}(q,\dot{q}) = \mathcal{T}(\dot{q}) - \mathcal{V}(q), \qquad (2)$$

$\mathcal{L}$ is the Lagrangian, $\mathcal{F}(\dot{q})$ is the Rayleigh dissipation function, $\mathcal{M}$ is a constant matrix, u is the control vector and Q_ζ represents disturbances. The EL equation (1) is written in dependence of the displacement q and the velocity $\dot{q}$ variables, $\mathcal{T}$ and $\mathcal{V}$ are respectively the kinetic energy and the potential energy.

C. Euler Lagrange model of boost converter

The modeling of switched power DC/DC converters is a fundamental issue in control design. Lagrangian and Hamiltonian dynamics approaches are well used in control theory of power converters. Euler Lagrange equation of boost converter can be written in the form of classical bilinear averaged model with state equation of the form $\dot{x} = f(x) + g(x)u$ [5]. Hamiltonian modeling approach is complementary and generalizes the Lagrangian dynamics equations. Our objective is modeling the boost converter with non ideal switches which gives a close behavior of the real converter. Energetic modeling reflects the energy transfer, consumption and dissipation of the different subcomponents of the converter.

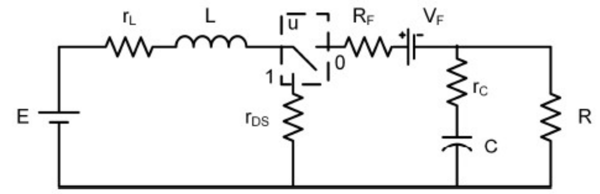

Fig. 1. Circuit equivalent of a boost converter with parasitic parameters.

The EL parametrization can be applied to hybrid systems and in our context to the class of switched regulated DC/DC converters. Introducing switch position parameters can cover all functioning modes of the converter and here we discuss only CCM. It has been demonstrated in [5] that EL equations of the switched converter can be written in the canonical form

$$\mathcal{D}\dot{x} + \mathcal{J}(u)x + \mathcal{R}x = \mathcal{E}, \qquad (3)$$

where x is the state space vector, u is the control signal, $\mathcal{D}$ is diagonal and positive definite matrix, $\mathcal{J}(u)$ is a skew-symmetric matrix, $\mathcal{R}$ is a diagonal semi-definite matrix and $\mathcal{E}$ is the input vector.

The figure 1 illustrates the boost converter with parasitic parameters. The state vector is $x = (x_1\ x_2)^t$. The variable x_1 represents the inductance current i_L (denoted by q_L) and x_2 is the capacity voltage v_C (equivalent to q_C/C).

The analysis of dynamical equations of Lagrange considers that u can take a discrete value in $\{0,1\}$. It is supposed here that the two switches (the diode and the transistor) are complementary.

Consider then $u = 1$. In this case we have two separate circuits and the Lagrange dynamics can be formulated as follows

$$\begin{aligned} \mathcal{T}_1(\dot{q}_L) &= \frac{1}{2}L(\dot{q}_L)^2, \\ \mathcal{V}_1(q_C) &= \frac{1}{2C}q_C^2, \\ D_1(\dot{q}_L,\dot{q}_C) &= \frac{1}{2}(r_C+R)(\dot{q}_C)^2 + \frac{1}{2}(r_L+r_{DS})(\dot{q}_L)^2. \end{aligned}$$

D is the dissipation structure. Consider now the case $u = 0$. It results one circuit with serial L and C. The corresponding Lagrange dynamics can be written as follows

$$\begin{aligned} \mathcal{T}_0(\dot{q}_L) &= \frac{1}{2}L(\dot{q}_L)^2, \\ \mathcal{V}_0(q_C) &= \frac{1}{2C}q_C^2, \\ D_0(\dot{q}_L,\dot{q}_C) &= \frac{1}{2}(r_L+R_F)(\dot{q}_L)^2 + \frac{1}{2}r_C(\dot{q}_C)^2 \\ &\quad + \frac{1}{2}R(\dot{q}_L-\dot{q}_C)^2. \end{aligned}$$

Clearly only the dissipation structure is affected by the position of switches. Therefore, it is possible to define the boost Lagrange dynamics as

$$\begin{aligned} \mathcal{T}_u(\dot{q}_L) &= \frac{1}{2}L(\dot{q}_L)^2, \\ \mathcal{V}_u(q_C) &= \frac{1}{2C}q_C^2, \\ D_u(\dot{q}_L,\dot{q}_C) &= \frac{1}{2}r_L(\dot{q}_L)^2 + \frac{1}{2}[(1-u)R_F + ur_{DS}](\dot{q}_L)^2 \\ &\quad + \frac{1}{2}r_C(\dot{q}_C)^2 + \frac{1}{2}R[(1-u)\dot{q}_L - \dot{q}_C]^2. \end{aligned}$$

D. Application of the canonical form

Applying the canonical form (3) we obtain

$$\mathcal{D}_B\dot{x} + (1-u)\mathcal{J}_B x + \mathcal{R}_B x = \mathcal{E}_B(u), \qquad (4)$$

where $\mathcal{D}_B = \begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix}$;
$\mathcal{J}_B = \begin{bmatrix} 0 & \frac{R}{r_C+R} \\ -\frac{R}{r_C+R} & C \end{bmatrix}$; $\mathcal{R}_B(u) = \begin{bmatrix} r(u) & 0 \\ 0 & \frac{1}{r_C+R} \end{bmatrix}$;
$r(u) = [r_L + ur_{DS} + (1-u)R_F + (1-u)^2(r_C||R)]$; [1]
$\mathcal{E}_B(u) = \begin{bmatrix} E-(1-u)V_F \\ 0 \end{bmatrix}$.

[1] $r_C||R$ designates parallel structure of resistances.

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III. CONTROL APPROACH OF THE BOOST CONVERTER

A. Introduction

The control of DC/DC converters can be classified in linear and nonlinear approaches. Linear approaches are varied and based on linearization of the model. State feedback, cascade PI are examples of such mehods. Most important nonlinear approaches are feedback linearisation, sliding mode, backstepping and passivity-based control. The lecturer can find applications of most of the mentioned methods on boost converter in reference [14]. PBC and Interconnection and Damping Assignment PBC (IDA-PBC) are suitable control methods for energetic state space models. These approaches are known by stabilization control laws and reducing the number of sensors.

B. Passivity-based control (PBC)

The minimum phase nature of the boost converter is reason of indirect control of the output voltage. However, the direct control of this latter can cause internal instability of the converter. The PBC approach is applied without the need of measuring the output voltage. It is someway a controller based on model "inverting", by dumping injection. The PBC approach is applied to the canonical form (4).

Let x_d the desired value of x and the error signal $\tilde{x} = x - x_d$. The PBC consists of injecting a suitable term to achieve a desired damping for the error system defined by

$$\mathcal{D}_B\dot{\tilde{x}} + (1-u)\mathcal{J}_B\tilde{x} + \mathcal{R}_{Bd}\tilde{x} = \Psi(u), \quad (5)$$

where $\mathcal{R}_{Bd} = \mathcal{R}_B + \mathcal{R}_{1B}$ and $\Psi(u)$ is a function $\neq 0$. The term $\mathcal{R}_{1B}$ can be chosen to be equal to $\begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix}$ so that we only introduce one damping parameter associated to the current expression (it is possible to introduce a second term $(1/R_2)$). The control strategy is based on letting $\Psi(u)$ to be equal to zero. This condition gives 2 equations where we have three unknown variables (u, x_{1d}, x_{2d})

$$\begin{aligned} L\dot{x}_{1d} + r(u)x_{1d} + (1-u)\frac{R}{r_C+R}x_{2d} & \\ -R_1(x_1 - x_{1d}) &= E - (1-u)V_F, \\ C\dot{x}_{2d} - (1-u)\frac{R}{r_C+R}x_{1d} + \frac{1}{r_C+R}x_{2d} &= 0. \end{aligned} \quad (6)$$

Let us fix $x_{1d} = I_L$. This implies

$$\begin{aligned} u &= \frac{R_1(x_1 - I_L) + E - V_F - ...}{(r_{DS} - R_F - r_C//R)I_L - V_F - \frac{R}{r_C+R}x_{2d}} \\ & \quad \frac{(r_L + R_F + r_C//R)I_L - \frac{R}{r_C+R}x_{2d}}{(r_{DS} - R_F - r_C//R)I_L - V_F - \frac{R}{r_C+R}x_{2d}}, \quad (7) \\ \dot{x}_{2d} &= (1-u)\frac{R}{(r_C+R)C}I_L - \frac{1}{(r_C+R)C}x_{2d}. \quad (8) \end{aligned}$$

Define the continuous variable u_{eq} which corresponds to the average of u during the switching period $(0 < u_{eq} < 1)$ and a novel variable ξ such that the equation (6) is verified using u_{eq} in place of u. The PBC control law of boost converter with parasitic parameters is [6]

$$\begin{aligned} u_{eq} &= \frac{R_1(x_1 - I_L) + E - V_F - ...}{(r_{DS} - R_F - r_C//R)I_L - V_F - \frac{R}{r_C+R}\xi} \\ & \quad \frac{(r_L + R_F + r_C//R)I_L - \frac{R}{r_C+R}\xi}{(r_{DS} - R_F - r_C//R)I_L - V_F - \frac{R}{r_C+R}\xi}, \quad (9) \\ \dot{\xi} &= (1-u_{eq})\frac{R}{(r_C+R)C}I_L - \frac{1}{(r_C+R)C}\xi. \quad (10) \end{aligned}$$

The discrete control signal u can be defined as follows

$$u = \frac{1}{2}[1 + sign(e)], \quad (11)$$

where e is the error signal defined by $\dot{e} = u_{eq} - u$. For simulation, the parameters of the boost converter are given in Table I.

TABLE I
THE BOOST PARAMETERS.

E	C	L	R	V_F	R_F
$12v$	$50\mu F$	$120mH$	50Ω	$0.8v$	$0.001m\Omega$
r_L	r_C	r_{DS}	I_L	V_C	F_{SW}
$5m\Omega$	$2m\Omega$	$60m\Omega$	$1.5A$	$30v$	$10KHz$

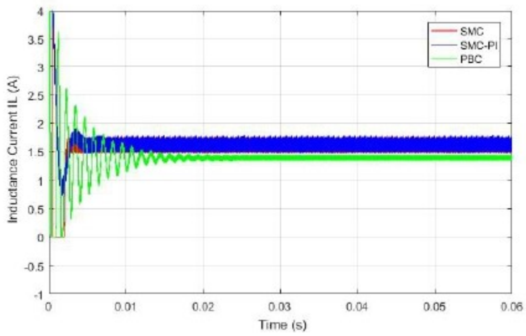

Fig. 2. Inductance current i_L for approaches (SMC, cascaded SMCPI and PBC).

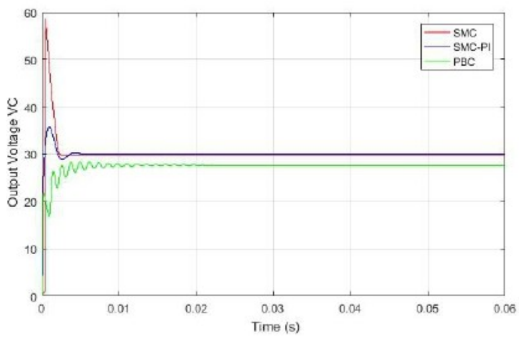

Fig. 3. Output voltage response v_C for approaches (SMC, cascaded SMCPI and PBC).

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Figures 2 and 3 illustrate a comparison of PBC approach (we choose $R_1 = 0.2$) with sliding mode control (SMC) and cascaded sliding mode-proportional integral control (SMCPI) [13]. We notice that the passivity-based control is done with the measurement of only the inductance current x_1 and the two other approaches SMC and SMCPI are done with two sensors (for x_1 and x_2). Although PBC approach shows steady state errors, in static regime, it gives an inductance current with low ripple value. The output voltage does not present any overshoot knowing that simulations are performed with zero initial states. For this simulation and like the other approaches, PBC is considered without parasitic parameters.

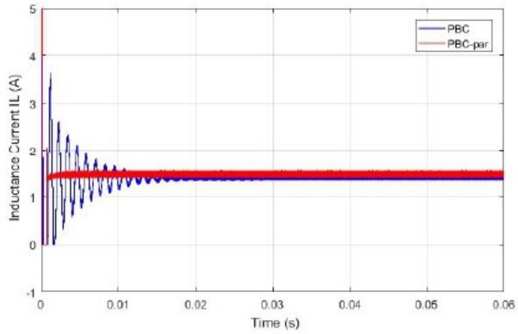

Fig. 4. Inductance current i_L for PBC and PBC-par control laws.

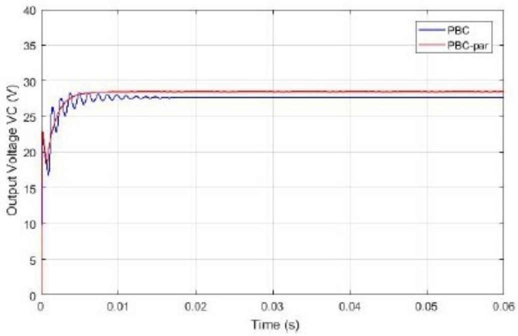

Fig. 5. Output voltage response v_C for PBC and PBC-par control laws.

C. Influence of parasitic parameters in PBC law

In the previous paragraph, we presented the PBC law with parasitic parameters. If we neglect these parameters in the control design, the control signal u_{eq} will be as follows [14]

$$u_{eq} = 1 + \frac{R_1 L(x_1 - I_L) - E}{\xi}, \quad (12)$$

$$\dot{\xi} = (1 - u_{eq})\frac{I_L}{C} - \frac{\xi}{RC}. \quad (13)$$

Figures 4 and 5 show the simulated output states with PBC (for PBC-par, we take equations (9) and (10) and for PBC the equations (12) and (13)) applied to the simscape model with parasitic parameters presented in Table I. One can

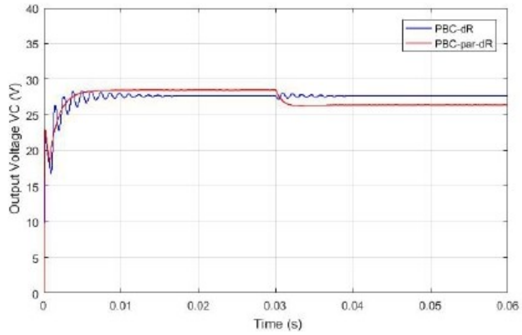

Fig. 6. Output voltage response v_C with load variation for PBC and PBC-par control laws.

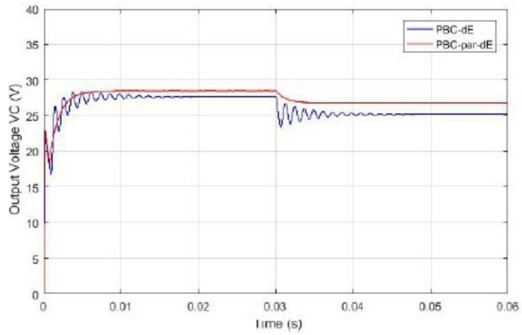

Fig. 7. Output voltage response v_C with Source E perturbation for PBC and PBC-par control laws.

observe steady state errors in the two cases. The dynamics of inductance current in PBC-par is less dumped. Figures 6 illustrates the effect of a load variation (R changes at 0.03 s from 50 ohm to 40 ohm). As can we see, in this case, PBC is robust vs. PBC-par. When we apply a perturbation of the DC source value E (at 0.03 s, E changes from 12v to 10v), the control algorithms are not robust (Fig. 7).

D. Adaptive Passivity-based sliding mode control (APBSMC)

1) Related works: Adaptive nonlinear control is well introduced in industry such as manipulators and motion control of rigid robots [7]. This reference introduces the first contribution to adaptive passivity-based control (APBC). There after many researchers have associated to APBC many other techniques to improve the quality of control and the precision of outputs in many recent industrial topics (quadrotor [8], spacecraft [9], synchronous motor [10]). These kinds of controls invoke some times other nonlinear approaches such as sliding mode and backstepping [11]. The technique of adaptive PBC can be based on algebraic parameter identification [12]. We consider in this paragraph the estimation of the input DC voltage source. Our contribution is a robust control law ensuring output voltage with very low steady state error. The robustness of the proposed controller is also simulated for load variation of the boost converter.

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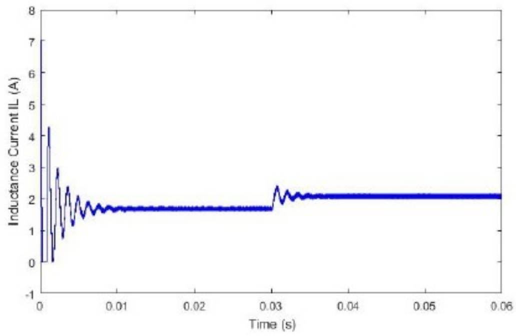

Fig. 8. Inductance current i_L with load variation (APBSMC approach).

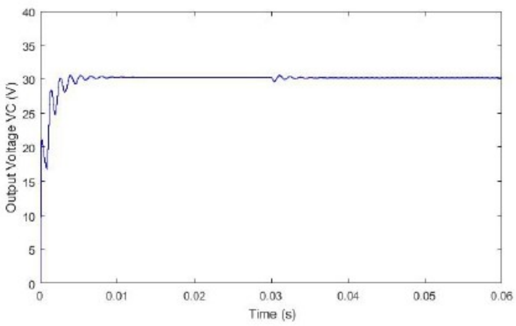

Fig. 9. Output voltage response v_C with load variation (APBSMC approach).

2) Control law of APBSMC: As stated before with only one sensor it is possible to control the boost converter taking into account parasitic parameters. We depict two important points: steady state error, which is absent in the two other approaches (SMC and SMCPI) and robustness. Introducing sliding mode control in our context will improve the precision of the system. There after applying an adaptive gain will resolve the robustness issue. Let us take the new control signal

$$u\prime_{eq} = u_{eq} - K_{SM} * sgn[K(\xi - V_C)] - K_{AD}(\hat{\theta} - E) \quad (14)$$

where K_{AD} is a feedback gain, $\hat{\theta}$ is an estimation of the parameter E and (K_{SM}, K) are gains introduced in the sliding mode.

The control law must drive the sliding manifold $\sigma(x) = K * (\xi - V_C)$ to zero in finite time. Choosing the Lyapunov function $V = \frac{1}{2}(\sigma(x))^2$, the sliding condition is $\dot{V} < 0$.

$$\dot{V} = \sigma(x)\dot{\sigma}(x) = K^2(\xi - V_C)\dot{\xi}$$

$$= K^2(\xi - V_C)((1 - u_{eq})\frac{I_L}{C} - \frac{\xi}{RC})$$
$$= K^2 \left(E - R_1 L(x_1 - I_L) + \frac{V_C}{RC}\xi - \frac{1}{RC}\xi^2 - \frac{V_C I_L (E - R_1 L(x_1 - I_L))}{C\xi}\right)$$
$$< K^2 \left(\frac{V_C + RC}{RC}\xi + \frac{V_C I_L R_1 L x_1}{C\xi} - \frac{V_C I_L E}{C\xi} - \frac{V_C R_1 L I_L^2}{C\xi} - \frac{1}{RC}\xi^2\right)$$
$$< -\eta/|\xi| < 0, \quad (15)$$

η is a positive constant.

The adaptive part of the control law is based on estimation of the parameter E which can be also a direct measurement of it. The parameters of simulation are $(R_1 = 0.2, K_{SM} = K_{AD} = 0.08, K = 1)$. Figures 8 and 9 show state responses with load variation (R changes at 0.03 s from 50 ohm to 40 ohm). Figures 10 and 11 prove the robustness of the proposed control approach with two perturbation values of the continuous source E (changes at 0.03 s from 12v to 11v and 10v).

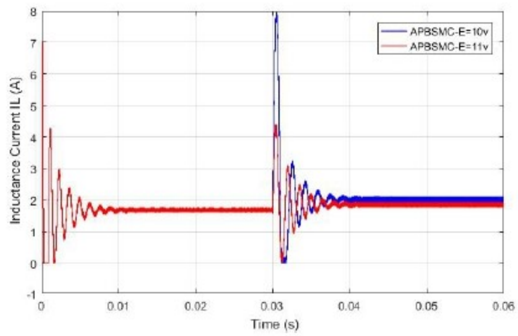

Fig. 10. Inductance current i_L with source E perturbations (APBSMC approach).

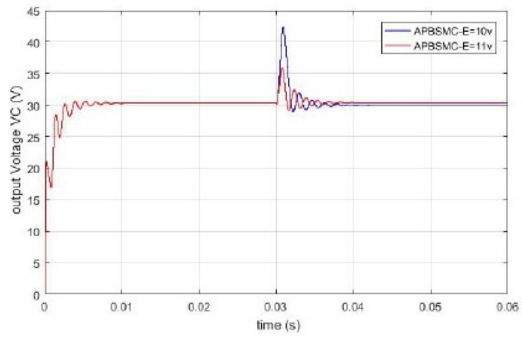

Fig. 11. Output voltage response v_C with source E perturbations (APBSMC approach).

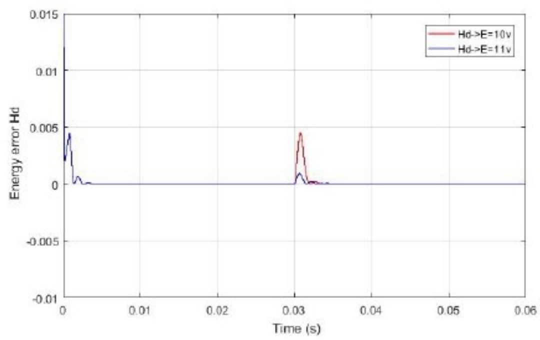

Fig. 12. Total stored error energy with source E perturbations.

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The total stored error energy is expressed as

$$\mathcal{H}_d = \frac{1}{2}\tilde{x}^T \mathcal{D}_B \tilde{x}, \tag{16}$$

with $\tilde{x} = x - x_d$. Figure 12 illustrates the dynamic evolution of this function with perturbation of continuous source E at 0.03 s (initial value is 12v). The time derivative of the $\mathcal{H}_d$ satisfies

$$\dot{\mathcal{H}}_d = -\tilde{x}^T \mathcal{R}_{Bd} \tilde{x} \leq -\frac{\alpha}{\beta}\mathcal{H}_d \leq 0, \tag{17}$$

α and β are positive constants which may be taken, respectively, as $\alpha = \min\{R_1, 1/R\}$ and $\beta = \max\{L, C\}$ [5]. Therefore $\mathcal{H}_d$ would be asymptotically stable to zero. A measure of the performance of the controlled system is obtained by using the integral of $\mathcal{H}_d$ [5]

$$\mathcal{I}_B = \int_0^\infty \mathcal{H}_d(\tau) d\tau. \tag{18}$$

This performance criterion is called WISSSE (weighed integral square state stabilization error) index. The values of WISSSE index calculated at $t = 0.06s$ are indicated in Table II (A:no perturbation, B:at t=0.03s E=11v, C:at t=0.03s E=10v).

TABLE II
WISSSE INDEX.

	A	B	C
$\mathcal{I}_B$	$6.60\ 10^{-6}$	$7.65\ 10^{-6}$	$1.11\ 10^{-5}$

E. Discussion

The accuracy of the converter's model is important in control design. Neglecting these parameters in the PBC control law provides steady state error but the control law is simpler to implement. Applying the PBC algorithm on a Matlab/Simulink simscape model reveals low robustness especially for DC source perturbations. The proposed APBSMC gives a satisfactory robust control with easy to fix parameters. The abrupt change of input source E can cause high dynamics of i_L and v_C. It is possible, by refinement of the controller parameters, to improve the simulation results. Even if it is not possible to do that, applying the simulated peak values of i_L in a short time of 0.002 s may be not harmful in real implementation. However the peak value of output voltage, with source perturbation, must be supported by the load system. The analysis of the stored energy of error shows the stability and the performance of the controlled system.

IV. Conclusions

The paper deals with the problem of robust control of boost converter with parasitic parameters. The proposed control approach provides zero steady state error and is robust against DC source perturbation and load variation. The control law is a superposition of three parts; the first corresponds to PBC, the second is based on the sliding mode principle and the third one is the adaptive part of the control. This last requires the estimation of the value of the DC source. Here we propose a direct measurement of this parameter. Simulation results proves the efficiency of the proposed controller. To evaluate the controller performance, we have used WISSSE index. Our future work consists of letting the controller with only one sensor i.e. the current sensor. This requires implementing an efficient algebraic estimator to detect the value of E and this will improve the reliability of the controller (to have less sensors in the structure of the controller).

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