On the Output Current Estimation of a DC-DC Multiplier Converter

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***Abstract*—This paper deals with the implementation of an output current estimator of a DC-DC Multiplier Boost Converter (MBC). A nonlinear adaptive observer that is able to estimate unknown parameters is employed. The estimation is based on an average reduced order dynamic model of the MBC. A real time platform is used for solving the dynamic equations of the adaptive observer. For estimation purposes, a nonlinear dynamic system is employed as an electric load. Experimental results show an excellent agreement between the actual output current of the converter and its corresponding estimation provided by the nonlinear adaptive observer.**

***Index Terms*—Power Electronics, DC-DC Boost Converter, Adaptive observer, Real-time.**

I. Introduction

In the recent years, new topologies for power electronics converters have been proposed. Some of these topologies have improved several features of the conventional power converters. This is the case of a new family of DC-DC Multiplier Converters that introduces new topologies based on the conventional Boost, Buck-Boost, Cuk and Sepic converters [1]. The main advantages of this new family of power electronics converters are: a high voltage gain without an extreme duty cycle, transformer-less, low voltage stress in switching devices and more output levels may be added without modifying the main circuit [1].

On the other hand, control theory has played an important role in the modeling and control of power electronics devices. In [2], dynamic models and a wide series of linear and nonlinear controllers for well-known power electronics devices are presented. In this paper we will focus on a particular case of the new family of DC-DC Multiplier Converters. In other words, we will be studying the DC-DC Multiplier Boost Converter (MBC), which is also known as DC-DC Multilevel Boost Converter [3].

In [3], the main features of the MBC are presented and the steady state equations are derived. In [5], a dynamic analysis of the MBC is performed and its corresponding state equations are presented. In the latter paper, an average reduced order nonlinear dynamic model for the MBC is proposed. The reduced order representation is a second order model which is able to approximate the dynamics of the MBC having an arbitrary number of capacitors (arbitrary number of levels) at the output. A key feature of the MBC that allows to obtain a reduced order model is the voltage balancing feature [4]. In this paper, we will be employing this reduced order model for estimating the transient behavior of the output current of the MBC.

In [6], it is shown a comparison between an algebraic parameter identification algorithm for the electric load of the conventional boost converter and its asymptotic estimation using state observers. In that case, a resistance is considered as the electric load connected at the output terminals. In the latter paper, it is also explained the advantages of the on-line estimation of unknown or time-dependent parameters/variables.

In [7], the estimation of the load torque and a passivity based controller for a traditional boost converter/DC-motor combination is presented. The load torque is estimated via an algebraic approach, this estimation is able provide robustness with respect to changes in that particular parameter. The implementation is based on the combination of the dynamic equations of the conventional boost converter and the dynamic equations of the permanent magnet DC-Motor.

An adaptive observer for cascade state affine systems was previously proposed in [8]. In [9], experimental results of the load torque estimation and some state variables of the DC-Motor were presented. In that paper, the utility of the adaptive observer was evident even when noisy measurements were involved.

In this paper, we present an experimental estimation of the output current of the recently proposed Multiplier Boost Converter (MBC). Instead of using a non-dynamic load (resistance) we employed a nonlinear dynamic system as an electric load connected at the converter terminals. In other words, the real time estimation is carried out for an electric load of the MBC (non-conventional converter) that has an unknown nonlinear dynamic behavior.

In this work, a reduced order adaptive observer obtained from [8], [9], is employed. The observer is implemented by using RTAI-Lab, a Linux-based real-time platform [10]. The output current of the MBC is considered as an unknown time-variant parameter. The output current of the MBC is measured just for validating the experimental results of the estimator. Experimental results show an excellent agreement between the actual output current of the converter and its estimation provided by the adaptive observer.

II. DC-DC Boost Converters

In this section, a brief description of some key features of the conventional DC-DC Boost Converter and the DC-DC Multiplier Boost Converter (MBC) is presented.

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A. Conventional DC-DC Boost Converter

An electric diagram of the so-called conventional DC-DC Boost Converter is shown in Fig. 1.

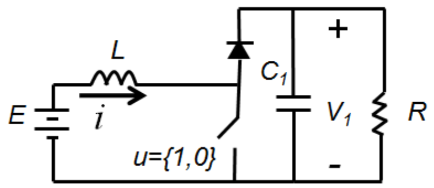

Fig. 1. Conventional DC-DC Boost Converter

By employing fundamental principles and considering the commutation states of the switch, the state equations of the conventional Boost Converter can be derived, [2]. They may be expressed as

$$L\frac{d}{dt}i = -(1-u_{av})V_1 + E \quad (1)$$

$$C_1\frac{d}{dt}V_1 = (1-u_{av})i - \frac{V_1}{R} \quad (2)$$

where $u_{av} = [0,1]$ is the average input or equivalently, the duty cycle of the converter. V_1 is the output voltage; E is the input voltage; i is the input current; L is the inductance at the input of the converter; C_1 is the capacitance at the output. R is the load resistance.

From (1)-(2), it is possible to obtain the following average steady state equations

$$V_1 = \frac{E}{(1-u_{av})} \quad (3)$$

$$i = \frac{V_1}{(1-u_{av})R} = \frac{i_o}{(1-u_{av})} \quad (4)$$

It is clear from expression (3) that during steady state operation, the input voltage E is multiplied by the voltage gain $1/(1-u_{av})$. In theory, the voltage gain tends to infinity as the duty cycle tends to one. However, the use of extreme duty cycles affects the efficiency of the converter [3]. In order to deal with the problem of the efficiency of the conventional converter without employing transformers or cascade converters, a new topology is proposed in [3]. It is called DC-DC Multiplier Boost Converter.

B. DC-DC Multiplier Boost Converter

The DC-DC Multiplier Boost Converter (MBC) is based on the well-known conventional DC-DC Boost Converter, see Fig. 2. It improves some of the issues of the conventional DC-DC Boost Converter

In order to increase the gain of the converter an array of diodes and capacitors is included as a part of the DC-DC Multiplier Boost Converter. The notation N represents the number of capacitors at the output of the converter.

For the purpose of explaining the voltage gain of the MBC, let us consider the dynamic equations of the average reduced order nonlinear model of the MBC previously presented in [5]

$$L\frac{d}{dt}i = -(1-u_{av})\frac{V}{N} + E \quad (5)$$

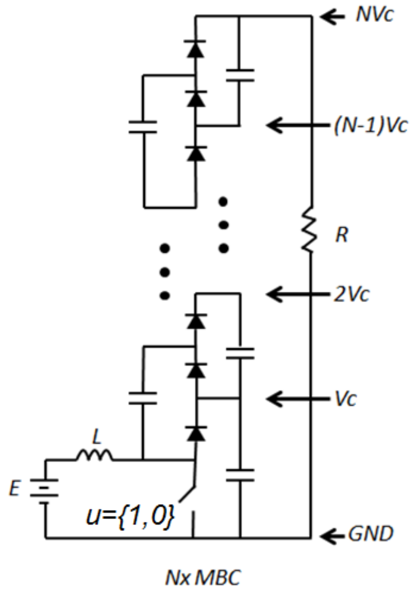

Fig. 2. DC-DC Multiplier Boost Converter

$$[C_{eq1}u_{av} + (1-u_{av})C_{eq2}]\frac{d}{dt}V = (1-u_{av})i - N\frac{V}{R} \quad (6)$$

where u_{av} is the average input or equivalently, the duty cycle of the converter; V is the output voltage or equivalently, the sum of the voltages across the capacitors at the output; E is the input voltage; R is the load resistance; i is the input current; L is the inductance at the input of the converter; C_{eq1} and C_{eq2} are some equivalent capacitances. From (5)-(6) the following steady state equations are obtained

$$V = \frac{N}{(1-u_{av})}E \quad (7)$$

$$i = \frac{NV}{(1-u_{av})R} = \frac{N}{(1-u_{av})}i_o \quad (8)$$

The voltage gain of a MBC having an arbitrary number of capacitors at the output is $N/(1-u_{av})$, see expression (7). It is evident that N also indicates the factor that modifies the original voltage gain, included in equation (3), of the conventional DC-DC Boost Converter. Since the voltage gain of the MBC is increased by a factor of N, no extreme duty cycles are necessary. This is a desirable feature for several applications such as renewable energy systems [1]. A detailed description of the advantages of the MBC compared to the conventional topology can be found in [3]. In addition, the dynamic behavior of the MBC is analyzed in [5] where the average reduced order nonlinear dynamic model is proposed and employed for indirect voltage control.

Let us consider a particular case of the *Nx* DC-DC Multiplier Boost Converter illustrated in Fig. 2, i.e. a MBC that has two capacitors (C_1 and C_2) at the output. This *2x* DC-DC Multiplier Boost Converter is depicted in Fig. 3.

If $C_1 = C_2 = C_3$, then the equivalent capacitances C_{eq1} and C_{eq2}, in expressions (5) and (6), are equal to C_1 and $2C_1$ respectively (see [5]); the quantity $C_{eq}(t)$ is defined here as

$$C_{eq}(t) = C_{eq1}u_{av} + (1-u_{av})C_{eq2} \quad (9)$$

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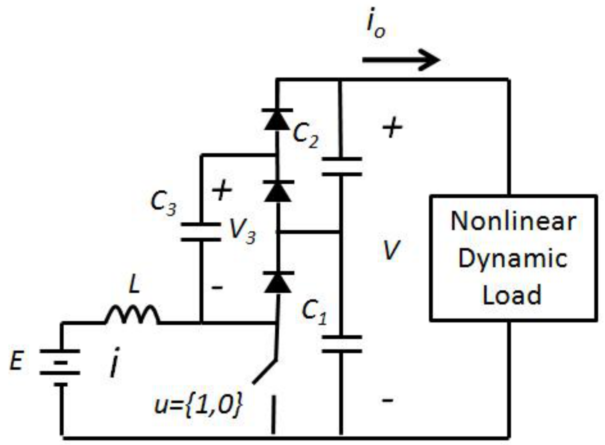

Fig. 3. *2x* DC-DC Multiplier Boost Converter

Using the above expression, equation (6) now becomes

$$\begin{array}{rcl} \dot{V} & = & \frac{(1-u_{av})}{C_{eq}(t)} i - \frac{N}{C_{eq}(t)} i_o \\ y & = & V \end{array} \tag{10}$$

where an output equation is also included. The resistance R has been eliminated from expression (10) by employing the following definition for the output current $i_o = V/R$. It is important to note that even though the nonlinear dynamic subsystem in (10) is presented here for a DC-DC Multiplier Boost Converter that has two capacitors at the output (i.e. *2x* MBC), expression (10) is valid for a DC-DC Multiplier Boost Converter containing any number of capacitors at the output (i.e. *Nx* MBC).

III. Nonlinear Adaptive Observer

Let us define the following dynamic system that has some uncertain parameters

$$\begin{array}{rcl} \dot{z} & = & A(u, y_m)z + \varphi(u, y_m) + \Phi(u, y_m)\theta \\ y_m & = & Cz \end{array} \tag{11}$$

where elements in $A(u, y_m)$, $\varphi(u, y_m)$ and $\Phi(u, y_m)$ are uniformly bounded continuous functions depending on the input u and the measured output y_m; θ is the vector of unknown parameters.

An adaptive observer for (11) that is able to estimate the no measurable state variables and the unknown parameters of the system was previously presented in [8]. It was derived to be applied to a class of cascade state affine systems. The equations of the observer are

$$\left\{ \begin{array}{rcl} \dot{\hat{z}} & = & A(u, y_m)\hat{z} + \varphi(u, y_m) + \Phi(u, y_m)\hat{\theta} \\ & & +\{\Lambda S_\theta^{-1}\Lambda^T C^T + S_z^{-1}C^T\}\Sigma(y_m - C\hat{z}) \\ \dot{\hat{\theta}} & = & S_\theta^{-1}\Lambda^T C^T \Sigma(y_m - C\hat{z}) \\ \dot{\Lambda} & = & \{A(u, y_m) - S_z^{-1}C^T C\}\Lambda + \Phi(u, y_m) \\ \dot{S}_z & = & -\rho_z S_z - A(u, y_m)^T S_z - S_z A(u, y_m) + C^T \Sigma C \\ \dot{S}_\theta & = & -\rho_\theta S_\theta + \Lambda^T C^T \Sigma C \Lambda \end{array} \right. \tag{12}$$

where $S_z(0) > 0$ and $S_\theta(0) > 0$; ρ_z and ρ_θ are sufficiently large positive constants; Σ is a bounded positive definite matrix. The gain associated with the estimation of the state vector of the system contains S_z; it is calculated as a solution of $\dot{S}_z = -\rho S_z - A(u, y_m)^T S_z - S_z A(u, y_m) + C^T \Sigma C$. In addition, $S_\theta^{-1}\Lambda^T C^T \Sigma$ is the gain associated with the estimation of the vector of unknown parameters.

For the purpose of implementing the nonlinear adaptive observer, a reduced order system will be employed. In other words, instead of considering the state equation that can be derived from expressions (5)-(6), we will be using the dynamic system defined by (10). The corresponding observer is a fifth order dynamic system, i.e.

$$\left\{ \begin{array}{rcl} \dot{\hat{z}} & = & \varphi(u, y_m) + \Phi(u, y_m)\hat{\theta} + (S_\theta^{-1}\Lambda^2 + S_z^{-1})(y_m - \hat{z}) \\ \dot{\hat{\theta}} & = & S_\theta^{-1}\Lambda(y_m - \hat{z}) \\ \dot{\Lambda} & = & -S_z^{-1}\Lambda + \Phi(u, y_m) \\ \dot{S}_z & = & -\rho_z S_z + 1 \\ \dot{S}_\theta & = & -\rho_\theta S_\theta + \Lambda^2 \end{array} \right. \tag{13}$$

using equations (10)-(12), it is easy to show that

$$A(u, y_m) = 0\ ; \quad \varphi(u, y_m) = \frac{(1 - u_{av})}{C_{eq}(t)} i$$

$$\Phi(u, y_m) = -\frac{N}{C_{eq}(t)}$$

where the output voltage V of the MBC is the measurable output variable and the only one state variable of the subsystem to be observed, i.e. $z = V = y = y_m$; it also clear that $C = 1$; the parameter to be estimated is output current of the MBC or equivalently, $\theta = i_o$. The inductor current i is considered as a measurable (known) variable; we also consider that $\Sigma = 1$. For the test presented in the next section the input $u = u_{av}$ is an arbitrary value that may be also defined by a control law.

IV. Experimental results

In order to estimate the output current of the MBC, the observer in (13) was solved in real-time by employing the RTAI-Lab platform (see [10]). The estimation of the output current of the MBC may be accomplished with either a linear or nonlinear electric load connected at the output of the MBC. In our test bench, a nonlinear dynamic system is connected as an electric load. During this test, the duty cycle u_{av} was changed arbitrarily to initiate transient behavior of the output voltage and the output current. These variations of the duty cycle are illustrated in Fig. 4. The input current of the MBC (inductor current) and the output voltage of the MBC were measured by using standard methods; these measurements are shown in Fig. 5 and Fig. 6. The actual output current of the MBC was measured for validation purposes. The comparison between the measured and the estimated output current is shown in Fig. 7. It is clear that the observer was able to estimate the output current of the MBC. It is important to note that the estimation is based on an average reduced order model of the MBC. The experiment demonstrates the utility of this approximate model of the MBC for parameter estimation purposes. In this test, the experimental values for the additional parameters of the MBC are: $L = 250\mu H$, $C_1 = C_2 = C_3 = 222.2\mu F$, $N = 2$, $E = 9\ volts$. The initial conditions for the observer were chosen as $S_z(0) = 1$, $S_\theta(0) = 1$, $\hat{z}(0) = 0$, $\Lambda(0) = 1$, $\hat{\theta}(0) = 2$, $\rho_z = \rho_\theta = 1000$. On the other hand, the initial conditions for the MBC are $z(0) = V(0) = 25$, $\theta = i_o(0) = 0.8$.

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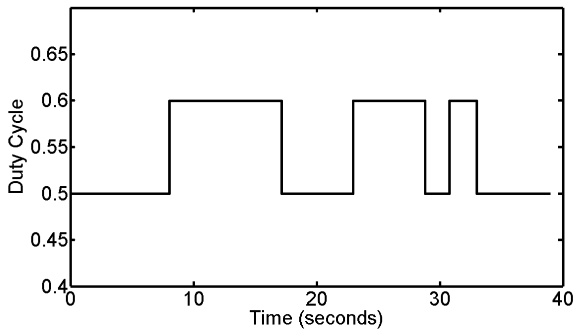

Fig. 4. Experimental arbitrary variations of the duty cycle

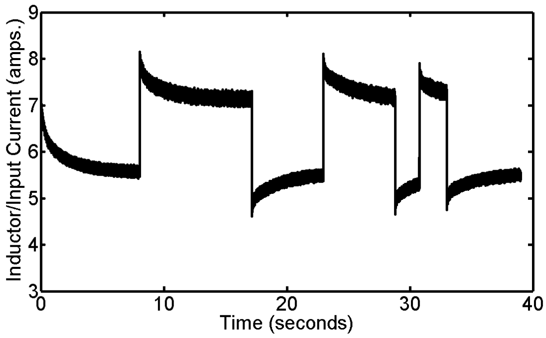

Fig. 5. Measured Input Current of the MBC

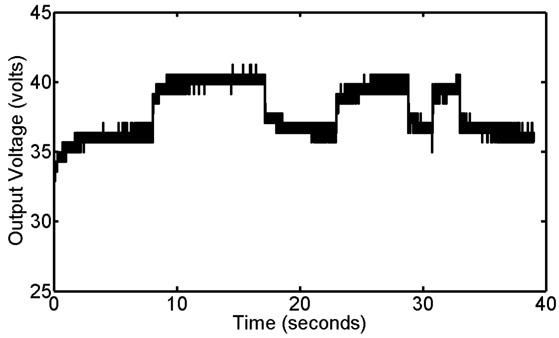

Fig. 6. Measured Output Voltage of the MBC

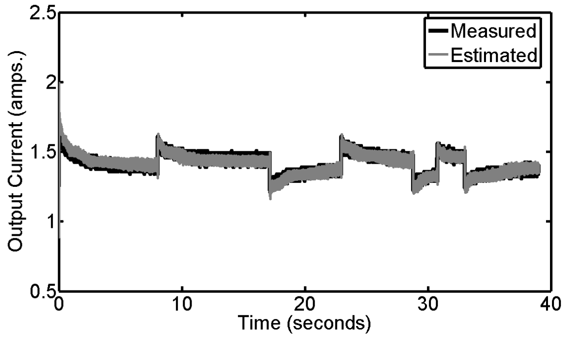

Fig. 7. Measured and Estimated Output Current

V. Conclusion

Experimental results show a good agreement between the actual output current of the converter and its estimation calculated by an adaptive observer. The average reduced order dynamic model of the MBC was employed. Even though, the average reduced order dynamic model is an approximation of the average full-order dynamic model of the MBC, it proved to be useful in the estimation of the dynamics of the output current. This work presented a contribution related to a parameter estimation for a recently proposed DC-DC Boost Converter. In future works, a reliable estimation of the output current may provide robustness and disturbance rejection in a closed loop implementation.

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