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Performances and Robustness Assessment of Sliding Mode Control Applied to a High Frequency Switched Parallel Three-Cell DC-DC Converter

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Abstract— **In the field of strong currents with high switching frequencies, new structures based on the combination of components have been developed. Among them, we find the parallel multicellular converters.**

This paper features a variable structure non-linear sliding mode controller (SMC) for closed loop control of DC-DC three-cell buck converter feeding parameters uncertainties and load disturbance, in order to overcome the design constraints and to mitigate the undesired transient response.

First, a nonlinear system modelling is derived for open-loop Buck converter with state variables of the input current and the output voltage. The model is extended for the closed-loop system while employing a Sliding Mode Control (SMC) solution. After the initial analysis of this converter, we utilize MATLAB/Simulink packages to analyse detailed performances as important parameters are varied.

Simulations are carried-out on the three-cell Buck converter to assess the performances and the robustness of the proposed control approach. Indeed, featuring robustness and high accuracy, they cope with system uncertainty keeping a properly chosen constraint by means of high-frequency control switching.

Keywords— **DC-DC converter, High switched devices, Multicellular converter, Sliding mode control, Buck converter, Robustness**

I. INTRODUCTION

Power electronics are currently embedded in all electric devices; they play an important role in the modern-day electronics and electrical applications. The development in the power electronics field is the result of the current energy challenges that require power converters working with higher voltages and currents. Among the most characteristic elements of this development, the conception of new power converters topologies is an important topic.

Design of such converters is a challenge for electrical engineers due to the use requirements and the inherent nonlinear nature. All the converters have few requirements like high density which leads to smaller size, high efficiency which leads to low losses and robust to any changes in the input or output [1]. For surpassing the problem of high frequency, a new class of power converter appeared: the multicellular converter [2], [3]. Multicellular conversion has inherent advantages that makes it an increasingly attractive solution which can be considered for any application. It provides more degrees of freedom to the designer, but it also makes design more complicated since many options can be considered. Indeed, a significant increase in the current required by the load can be satisfied by driving several branches of the power supply simultaneously.

Thus, when the phase-shifted currents add up to form the output current, the ripple ratio is significantly reduced with a frequency n times greater than the switching frequency [4]. For this reason, it seems important to develop an approach that allows fast evaluation of several solutions with different numbers of series and parallel cells, the particular case of one cell in series and one cell in parallel corresponding to the case of standard two-level conversion [5].

Besides, modelling is a very important step for control laws and since DC–DC converters are nonlinear systems, they represent a big challenge for control design. The control methodologies for DC-DC converter are designed for tight regulation of out-put voltage amidst varying input and loading conditions, keeping in mind the unpredictable nature of such diverse plants. Meanwhile, the fixed-frequency PWM control is by far the most popular control technique used for the regulation of DC–DC converters that assume two specific forms, namely voltage feedback control and current-programmed control and operate optimally only for a specific condition. The limit of this strategy results in the small-signal assumptions, the converter's behaviour cannot be adequately captured when there is a large transient.

The failure of conventional linear and partial nonlinear control schemes, namely, PWM voltage and PWM current-mode control, to operate satisfactorily in large-signal operating conditions, is the main motivation for investigating alternative methods of controlling DC–DC converters.

An overview of the various control methodologies being considered and have been found to have potential applications in DC–DC converters that require very high performance in dynamical response such the sliding mode control that offers excellent large-signal handling capability.

A variable structure non-linear control scheme like the sliding mode control acts as a perfect fit for controlling a

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highly non-linear and time varying system like the DC-DC switched mode converter. SMC is a powerful method that is able to yield a very robust closed-loop system under plant uncertainties and external disturbances [6]. This controller ideally operates at an infinite switching frequency such that the controlled variables can track a certain reference path to achieve the desired dynamic response and steady-state operation [7], ant it is adopted to suppress the input disturbance and reduce the effects from the load variation [8]. Moreover, the sliding mode control may reduce the complexity of feedback control design through decoupling of system into the independent subsystems of lower dimension. Because of these properties, the diverse applications of the sliding mode control methodology can be found in the areas of electric motors, manipulators, power systems, mobile robots, spacecraft and automotive control. However, the main drawback of the sliding mode control is undesirable oscillations having finite amplitude and frequency due to the presence of unmodelled dynamics or discrete time implementation. This destructive phenomenon, so-called ‘chattering’, may lower control accuracy or incur an unwanted wear of a mechanical component. In the literature, various solutions to reduce the chattering have been studied [9], [10], [11]. Several publications have appeared in recent years have shown interest in utilization of the relative design simplicity and the robustness of SMC to deal with DC-DC converter control problem [12]-[16].

A DC-DC converter controlled using sliding mode theory yields large signal stability counter to the linear conventional controllers which guarantee desired performance against only small perturbations in input voltage or load current [17], [18].

Hereinafter, section 2 deals with the model of the converter and the concept of the conventional sliding mode control methodology for DC-DC buck converter. While the following section presents the simulation results and brief discussion of the same. Finally, the conclusion is reported in section 4 that draws comprehensive inferences from the work performed and the observations made.

II. CONVERTER MODELLING AND SMC CONCEPTION

DC-DC converters constitute a particular class of nonlinear, time-varying systems. The periodic repetition of the sequence absorption-transfer results in a cyclical variation of the converter topological configuration, which leads to a repetitive sequence of two or three circuit structures whose time durations are not constant due to the modulation of TON and/or TOFF. Therefore, DC-DC switching converters can be considered as variable structure systems and the voltage regulation has been traditionally undertaken by means of linear control based on a small signal model of the converter in the frequency domain. The sliding-mode approach based on the equivalent control method is particularly appropriate for designing the regulation loop of a DC-DC switching converter [19].

Figure.1 depicts a basic topology of the buck converter, in which V_{in} is the input DC voltage; L is the filter inductor; C is the output capacitor; R_L is the equivalent load. Then the system dynamics of the buck converter can be expressed as:

$$L\frac{di_L}{dt} = -i_L - V_{out} + u.V_{in} \quad (1)$$

$$C\frac{dV_{out}}{dt} = i_L + \frac{V_{out}}{R_L} \quad (2)$$

Where i_L is the inductor current; V_{out} is the output capacitor DC voltage; u is the control input.

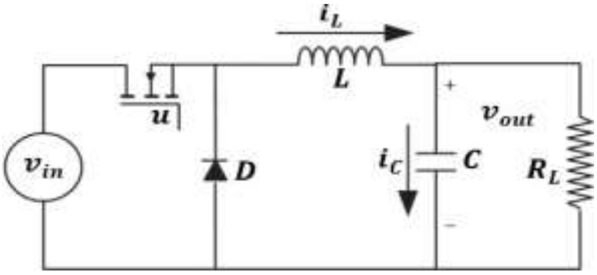

Fig. 1 Basic topology of the buck converter

The considered buck converter is a second order converter, with Single Input Single Output (SISO) structure, where, the cells are associated in parallel with R load, realized in MATLAB/SIMULINK.

A. *Multicellular Converter*

Multicellular converter consists of phases, where each cell contains two complementary power electronics components and it is controlled by a binary switch.

As shown in Figure.2, a 3-phase converter feeds a single load assumed to be resistive.

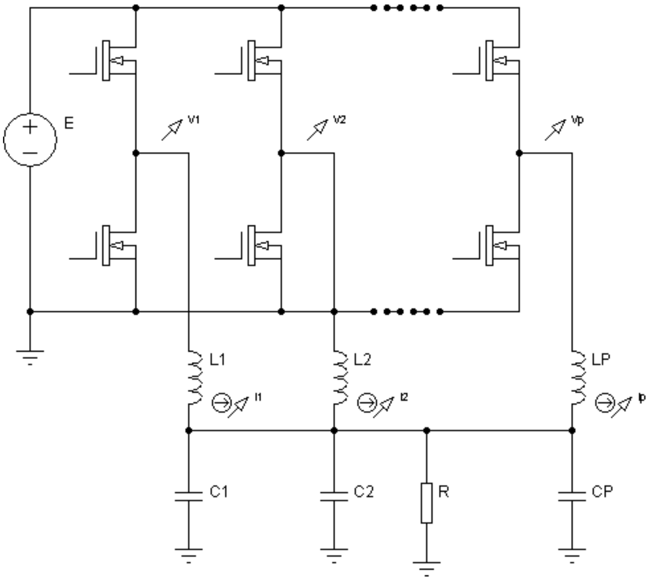

Fig. 2 Studied p-cells Buck Converter

Our studied multiphase step-down power converter is composed of several DC/DC Buck converters with an output capacitor. A 3-phase converter can be modelled by the following set of differential equations:

$$L\frac{di_k}{dt} = -i_k - V_{out} + V_{in}u_k; \quad k = 1,2,3 \tag{3}$$

$$L\frac{dV_{out}}{dt} = \sum_{k=1}^{3} i_k - \frac{V_{out}}{R} \tag{4}$$

Where i_k is the circulating current through the 3-phase, V_{out} the output voltage and u_k the k-phase control input which takes values in the set {0,1}. Identical phase parameters are assumed, namely, inductances (L), capacitors (C) and input voltages (V_{in}).

Each cell comprises a chopper DC-DC converter and a single protection transistor connected in a high-voltage portion of the converter thereby enabling any of the cells to be taken out of service independently of the other cells while minimizing power consumption in normal operation.

Figure 3 illustrates the configuration adopted of the three-cell step down DC-DC converter associated in parallel and realized in MATLAB/Simulink environment.

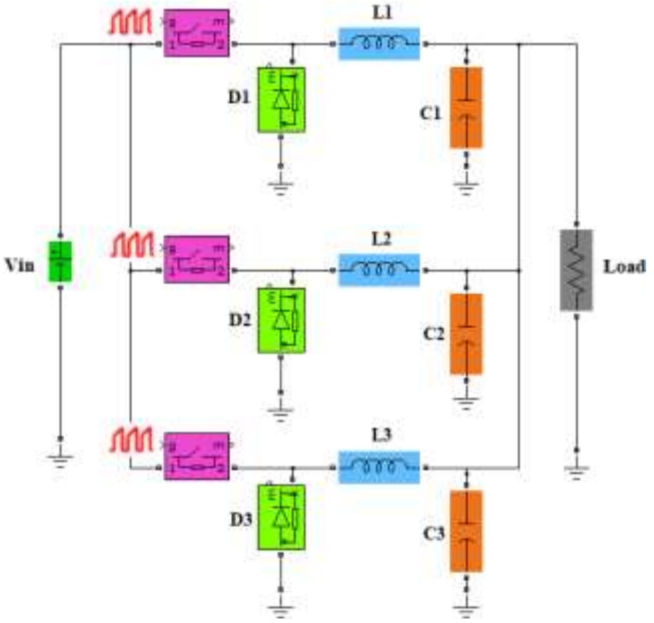

Fig. 3 Three-cell Buck converter associated in parallel

To illustrate the operating principle, the state-space description of the buck converter under SM voltage control is represented.

$$x_1 = V_{ref} - \alpha V_{out} \tag{5}$$

$$x_2 = \dot{x}_1 = -\alpha\frac{dV_{out}}{dt} = \frac{\alpha}{C}\left(\frac{V_{out}}{R} - \int\frac{u.V_{in} - V_{out}}{L}dt\right) \tag{6}$$

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\frac{1}{LC} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ -\frac{\alpha V_{in}}{LC}\end{bmatrix}u + \begin{bmatrix}0\\ \frac{V_{ref}}{LC}\end{bmatrix} \tag{7}$$

B. *Conventional Sliding Mode Control*

Sliding modes are obviously adopted as the three-cell converter has at least one discrete control variable. We start by choosing the sliding surfaces whose number and shape are determined to ensure a convergence of output values to the reference values [20]. The control aims to ensure the convergence of switching surfaces Si to zero, to allow the reaching of the state variables to their references.

For an SM voltage controller, the switching function u can be determined from the control parameters x_1 and x_2 using the state trajectory computation:

$$S = \beta x_1 + x_2 = Jx \tag{8}$$

Where β is a positive parameter, J =[β,1]; and x =$[x_1,x_2]^T$.

By enforcing S =0, a sliding line with gradient β can be obtained. The purpose of this sliding line is to serve as a boundary to split the phase plane into two regions.

The choice of the surface is based on the objectives to be achieved, which generally represent the desired behaviour of the quantities to be regulated.

$$S = k_{P1}(V_{ref} - \alpha V_{out}) + k_{P2}i_C \tag{9}$$

Where k_{P1}=1/RC and k_{P2}= -α/C. In the above equation, the terms (V_{ref} − α V_{out}) and i_C are the feedback state variables from the converter that should be amplified by gains k_{P1} and k_{P2}, respectively, before a summation is performed. Synchronization among phases can be attained through the 3 switching surfaces.

It is simpler to reconfigure the switching function to the following description:

$$S = \frac{C}{\alpha}\beta x_1 + \frac{C}{\alpha}x_2 = Q.x \tag{10}$$

where $Q = \begin{bmatrix}\frac{C}{\alpha}\beta & \frac{C}{\alpha}\end{bmatrix}$ and $x = \begin{bmatrix}x_1 & x_2\end{bmatrix}^T$ then we get

$$S = \frac{1}{\alpha R}(V_{ref} - \alpha V_{out}) - i_C \tag{11}$$

Thus, the practical implementation of S becomes independent of C, thereby reducing the amplification of the feedback signals. The control law generated by a sliding

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where L, C and R are the inductance, capacitance and instantaneous load resistance, respectively; V_{ref}, V_{in}, and αV_{out} are the reference, input voltage, and output voltage, respectively; u = 1 or 0 is the switching state of power switch SW. Therefore, the model can be obtained as

mode controller is composed of two essential parts. The first is called equivalent control variable denoted U_{eq}, obtained by the exact linearization and serves to maintain the state on the sliding surface. The second discontinuous control quantity U_n developed to verify the convergence condition. To determine the two control quantities, calculate the derivative of the expression of the sliding surface according to the parameters

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of the system model given by (7). The derivative of the sliding surface is:

$$\dot{S}(x) = \frac{\partial S}{\partial t} = \frac{\partial S}{\partial x}\frac{\partial x}{\partial t} \qquad (12)$$

$$\dot{S}(x) = \frac{\partial S}{\partial x}(A(x,t) + B(x,t).U_{eq}) + \frac{\partial S}{\partial x}B(x,t).U_n \qquad (13)$$

$$S(x) = \frac{\partial S}{\partial x}(A(x,t) + B(x,t).U_{eq}) + \frac{\partial S}{\partial x}B(x,t).U_n \qquad (13)$$

Assuming that during slip mode and during steady state establishment the slip surface is zero, this implies that its derivative and the discontinuous control magnitude are also zero. The expression of the equivalent order is then the following:

$$U_{eq} = -\left(\frac{\partial S}{\partial x}B(x,t)\right)^{-1} \cdot \frac{\partial S}{\partial x}A(x,t) \qquad (14)$$

According to (14), the existence of the equivalent order depends on the term ∂S/∂x B(x,t) which must not be zero. In this case, by replacing the expression of the equivalent command in (13), we can write:

$$U_n = -U_{Max}.sat(S) \qquad (15)$$

$$sat(S) = \begin{cases} \frac{S}{1} & \text{if } |S| \leq 1 \\ \text{sgn(S)} & \text{if} |S| \leq 1 \end{cases} \qquad (16)$$

$$\text{sgn}(S) = \begin{cases} -1 & \text{if S} \prec 1 \\ 1 & \text{if S} \succ 1 \end{cases} \qquad (17)$$

U_{Max}: Positive constant and l the threshold width of the saturation function.

The specification of the switching state for each sector in the case of a second-order system like the buck converter can be considered as for u=1 must be employed so that the trajectory is directed toward the sliding line. Conversely, when the phase trajectory is at any position below sliding line, u=0 must be employed for the trajectory to be directed toward the sliding line. This forms the basis for the control law:

$$u = \begin{cases} 1 = 'ON' & \text{when S} \succ 0 \\ 0 = 'OFF' & \text{when S} \prec 0 \end{cases} \qquad (18)$$

The system trajectory will eventually reach the sliding line, and the control law in (18) provides the general requirement that the trajectories will be driven toward the sliding line.

To ensure that the trajectory is maintained on the sliding line, the existence condition, which is derived from where ξ is an arbitrarily small positive quantity. Substituting (7) and (18) into (20), the inequalities become

$$\lambda_1 = \left(\frac{C}{\alpha}\beta - \frac{1}{\alpha R}\right)x_2 - \frac{1}{\alpha L}x_1 + \frac{V_{ref} - \alpha V_{out}}{\alpha L} \prec 0 \qquad (21)$$

$$\lambda_2 = \left(\frac{C}{\alpha}\beta - \frac{1}{\alpha R}\right)x_2 - \frac{1}{\alpha L}x_1 + \frac{V_{ref}}{\alpha L} \succ 0 \qquad (22)$$

Where

$$\begin{cases} \lambda_1 = Q.x & 0 \prec S \prec \xi \\ \lambda_2 = Q.x & -\xi \prec S \prec 0 \end{cases} \qquad (23)$$

Hence, to ensure that β is high enough for fast dynamic response and low enough to maintain a large existence region, it is sufficient to set

$$\beta = RC \qquad (24)$$

On the other hand, if a faster dynamic response is desired, β can be reduced, as long as the existence condition of the system is met. For this purpose, it is necessary to take into consideration the operating condition of the converter.

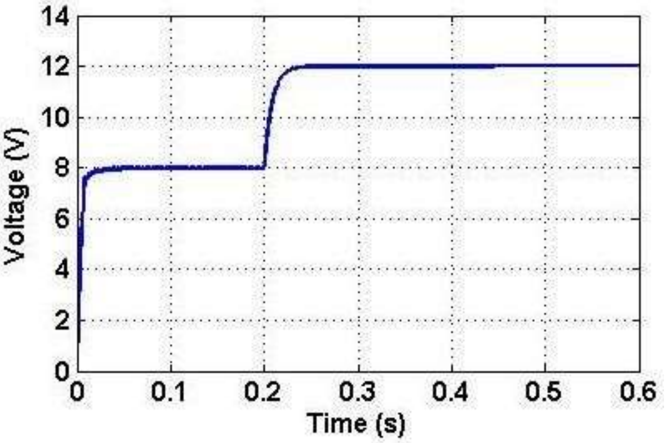
III. SIMULATION RESULTS

A. Simulation Results and Robustness Assessments

In order to illustrate the performance of the proposed control, we considered a three-cell converter connected to an R load. The performances of the developed sliding mode control were verified through simulation using MATLAB software.

1) Robustness versus power reference variation

Robustness test versus the power reference value changes are illustrated by figures 4 and 5. Indeed, at t = 0.2 s, V_{ref} is slightly changed. According to these results, it is obvious that the control objective is fulfilled.



Lyapunov's second method to determine asymptotic stability, must be obeyed:

$$\lim_{S\to 0} S.S \quad 0 \tag{19}$$

Thus, by substituting the time derivative of (8), the condition for SM control to exist is:

$$\dot{S} = \begin{cases} J\dot{x} \prec 0 & \text{for } 0 \prec S \prec \zeta \\ J\dot{x} \succ 0 & \text{for } -\zeta \prec S \prec 0 \end{cases} \tag{20}$$

Fig. 4 Simulation result for output voltage due to a step change in Vref from 8V to 12V

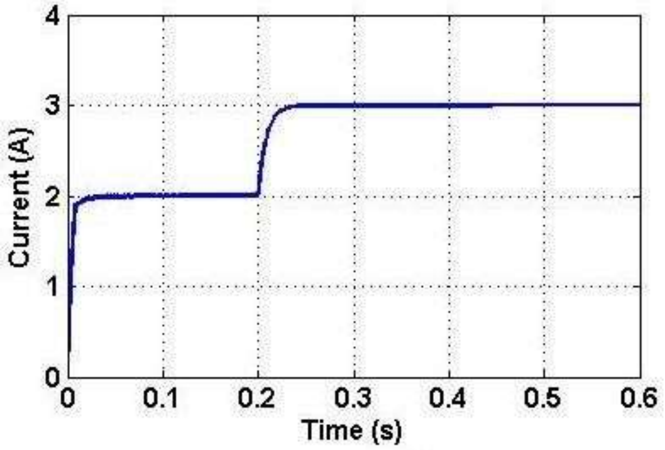


Fig. 5 Simulation result for load current due to a step change in Vref from 8V to 12V

2) Robustness versus load resistance variations

To test the performance of the proposed controller, a comprehensive simulation under step load change (variation of 50%) with constant input voltage was tested. The reference output voltage was set to 12 V and the load demand was set to 3A.

The situation where the load changes suddenly from one value of load resistance to another is considered. This particularly interesting because it is a typical problem for power electronics, where the power supply is supposed to compensate quickly for the load variation.

Robustness test versus the load resistance are illustrated by figures 6 and 7.

These figures show that the state variables exhibit a transient but the promptly converge to their respective reference.

The input voltage was fixed to 24 V, a step load change occurs, The load resistance changes from 2Ω to 4Ω. The drop in the regulated output voltage went up by 0.5 V and it took about 0.003s for it to settle down at 12 V.

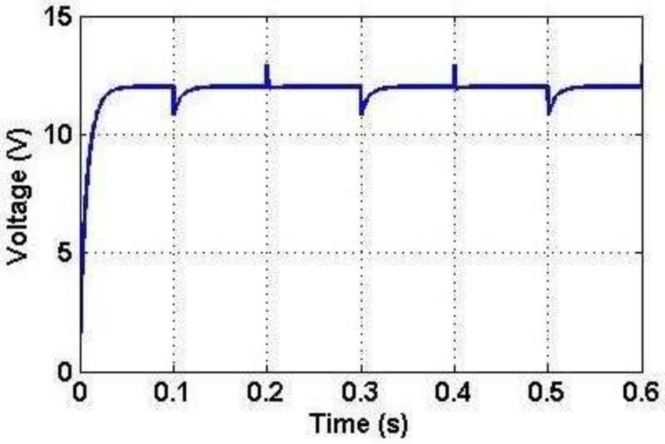


Fig. 6 Output voltage response with a variation of 50% of the load resistance

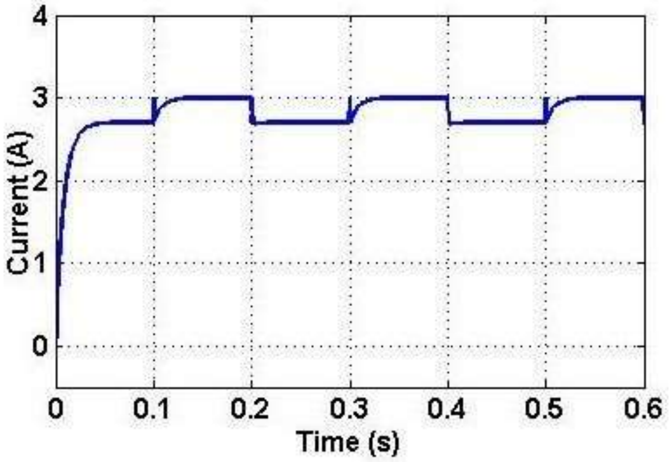


Fig. 7 Load current response with a variation of 50% of the load resistance

According to these results, it can be noticed that the performances of the proposed control for load variation are satisfactory.

Then, the above two tests confirm the robustness of the proposed sliding mode control strategy for the three-cells converter. It rejects external perturbation and some controlled system parameters variations. The robustness of the proposed SMC was tested with a load resistance variation of 50%.

3) Robustness versus input voltage variations

Finally, the input voltage was varied to corroborate the line regulation of the converter. To test the robustness of the developed control, a first disturbance is assigned to the level of the supply voltage. The converter is initially powered by a input voltage V_{in} = 11.5V which varies at instant t = 0.1s to reach 12V

Figures 8 and 9 summarize the results of this test. There is a very brief transient that lasts a few ms followed by a steady state giving voltage values V_{out} proportional to the new value of V_{in}.

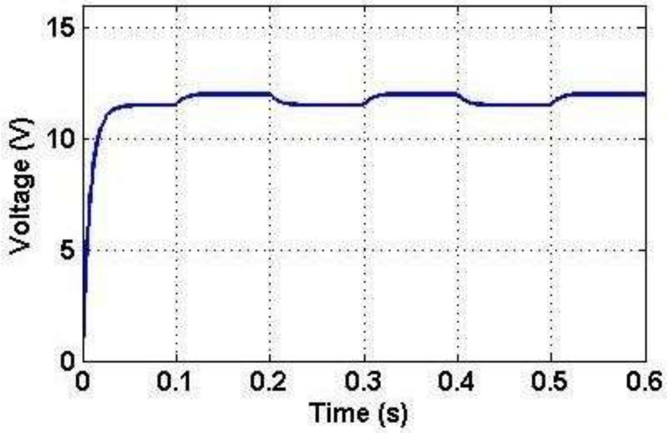


Fig. 8 Simulation results of the Output voltage response with a input voltage variation

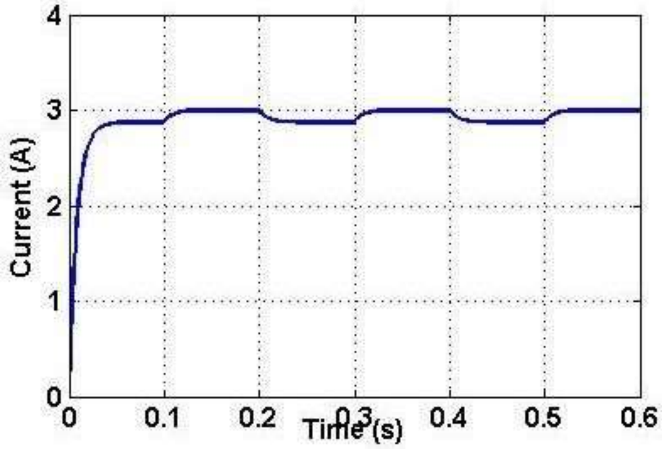


Fig. 9 Simulation results of the load current response with an input voltage variation

IV. CONCLUSIONS

A variable structure non-linear control technique has been presented and implemented successfully for a high switched three-cell DC-DC converter associated in parallel. The performance of dynamic evolution under step load change and step reference output voltage change condition has been tested, the proposed dynamic evolution controller outperforms a conventional sliding mode controller with disturbance rejection.

The main advantage of the SM converter is the simplicity in the con- troller's design and implementation. Unlike conventional current-mode and voltage-mode controllers, which require special techniques.

The carried-out simulations show very promising results in terms of reference tracking performances and robustness. They prove the appropriateness of sliding mode control for such kind of the system.

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