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On modeling and real-time simulation of a robust adaptive controller applied to a multicellular power converter

Introduction. *This paper describes the simulation and the robustness assessment of a DC-DC power converter designed to interface a dual-battery conversion system. The adopted converter is a Buck unidirectional and non-isolated converter, composed of three cells interconnected in parallel and operating in continuous conduction mode.* ***Purpose.*** *In order to address the growing challenges of high switching frequencies, a more stable, efficient, and fixed-frequency-operating power system is desired.* ***Originality.*** *Conventional sliding mode controller suffers from high-frequency oscillation caused by practical limitations of system components and switching frequency variation. So, we have explored a soft-switching technology to deal with interface problems and switching losses, and we developed a procedure to choose the high-pass filter parameters in a sliding mode-controlled multicell converter.* ***Methods.*** *We suggest that the sliding mode is controlled by hysteresis bands as the excesses of the band. This delay in state exchanges gives a signal to control the switching frequency of the converter, which, in turn, produces a controlled trajectory. We are seeking an adaptive current control solution to address this issue and adapt a variable-bandwidth of the hysteresis modulation to mitigate nonlinearity in conventional sliding mode control, which struggles to set the switching frequency. Chatter problems are therefore avoided. A boundary layer-based control scheme allows multicell converters to operate with a fixed-switching-frequency.* ***Practical value.*** *Simulation studies in the MATLAB / Simulink environment are performed to analyze system performance and assess its robustness and stability. Thus, our converter is more efficient and able to cope with parametric variation.* References 17, figures 6.

Key words: **multicellular converters, sliding mode control, high switching frequency, hysteresis modulation.**

Вступ. *У статті описується моделювання та оцінка надійності силового перетворювача постійного струму, призначеного для взаємодії із системою перетворення з двома батареями. Прийнятий перетворювач є односпрямованим і неізольованим перетворювачем Бака, що складається з трьох паралельно з'єднаних між собою осередків, що працюють в режимі безперервної провідності.* ***Мета***. *Для вирішення проблем, пов'язаних з високими частотами перемикання, потрібна більш стабільна, ефективна система живлення з фіксованою частотою.* ***Оригінальність***. *Звичайний регулятор ковзного режиму страждає від високочастотних коливань, викликаних практичними обмеженнями компонентів системи та зміною частоти перемикання. Отже, ми дослідили технологію м'якого перемикання для вирішення проблем інтерфейсу та комутаційних втрат, а також розробили процедуру вибору параметрів фільтра верхніх частот у багатоосередковому перетворювачі зі ковзним режимом.* ***Методи***. *Ми припускаємо, що ковзний режим управляється смугами гістерезису як надлишками смуги. Ця затримка обміну станами дає сигнал управління частотою перемикання перетворювача, який, своєю чергою, створює керовану траєкторію. Ми шукаємо рішення для адаптивного керування струмом, щоб вирішити цю проблему і адаптувати гістерезисну модуляцію зі змінною смугою пропускання для пом'якшення нелінійності у звичайному ковзному режимі керування, яке щосили намагається встановити частоту перемикання. Таким чином вдається уникнути проблем із деренчанням. Схема керування на основі прикордонного шару дозволяє перетворювачам з кількома осередками працювати з фіксованою частотою перемикання.* ***Практична цінність***. *Імітаційне моделювання у середовищі MATLAB/Simulink виконується для аналізу продуктивності системи та оцінки її надійності та стабільності. Таким чином, наш перетворювач ефективніший і здатний справлятися зі зміною параметрів.* Бібл. 17, рис. 6.

Ключові слова: **багатоосередкові перетворювачі, ковзне управління, висока частота перемикання, гістерезисна модуляція.**

Introduction. Designing a dual-battery 12/48 V conversion system is challenging because it requires careful management of power transfer from the 48 V rail to its 12 V rail [1, 2]. One option is to use a buck unidirectional DC-DC converter located between the 12 V and 48 V batteries. This converter can be used to step down the voltage and transfer power between batteries. The introduction of unidirectional DC-DC converters, simplifies design, reduces cost and encourages adoption in low-cost cars [3]. The power distribution network also has the ability to detect faults in auxiliary loads as well as turn these loads on and off. The power distribution network is implemented with two main systems: the auxiliary power system, which consists of a 2.4 W buck converter with current limiting control circuits at 12 V. The other system is the control system, which is developed using microcontrollers and autonomous controllers [4].

In addition, DC-DC power converters are ideal candidates in many applications such as electric vehicles, fuel cells and others. They have been the subject of much research over three decades [5-9]. The control of these converters has often been implemented using pulse width modulation and discrete component and integrated circuit techniques in different anterior research work that have reached its limits [10, 11]. Besides, nonlinear sliding mode controllers represent a very promising strategy for parallel multi-channel converters integrate control techniques with numerous sliding surfaces and an intrinsic variable. They are simple to develop, robust, and respond well in transient and steady conditions. Furthermore, they limit switching frequency variation, reduce inappropriate transient response, and achieve a proper balance of transient and stationary performance [12-14]. This drives us to propose a sliding mode controller implementation based on the hysteresis function. The technology is simple to use and does not necessitate the use of any additional auxiliary circuits or sophisticated computations. Previous research indicates that the main barriers to using sliding mode control are two interrelated factors: chatter and excessive activity of control actions [15-17]. The amplitude of chattering is clearly acknowledged to be linked to the magnitude of a discontinuous controller. These two issues can be dealt with concurrently, if the magnitude is limited to a minimal recommended levels determined by the sliding mode's existence criteria. In such a highly interesting context, we developed an adaptive sliding mode controller. It can be used to decrease chatter, with the purpose of ensuring an adaptive and dynamic control. The main concept behind the adaptive control technique is to create systems that display the same dynamic features under relevant uncertainty situations and adequate to overcome uncertainties and disturbances. This method will be thoroughly discussed in the remainder of our study. The body of the paper is structured as follows:

In the converter topology and mathematical model section, we will explain and model the adopted system. In the controller design section, we will examine the hysteresis modulation-based sliding mode controller. In the simulation results and stability analyses section, we will discuss the simulation findings and analyze the effectiveness of the control measures. And we will end with a conclusion.

Converter topology and mathematical model. Figure 1 depicts the multicell DC-DC buck converter under investigation. It consists of three identical modules coupled via a resistive load R and a filter capacitor C to a continuous DC input voltage source V_I. Each module is built around a power MOSFET S, an antiparallel diode D, and a filter inductor L. It's important to note that the parallel switching buck converter works in continuous conduction mode. In other words, the 3 cells are identical, each cell have the same value of the inductor L. The converter may be described by an equation system based on a mathematical model with mean values, and the system dynamics of the examined converter can be defined as follows:

$$L \cdot \frac{\mathrm{d}I_{Lj}}{\mathrm{d}t} = V_I \cdot D - V_O ; \qquad (1)$$

$$C \cdot \frac{\mathrm{d}V_O}{\mathrm{d}t} = I_L + \frac{V_O}{R} , \qquad (2)$$

where I_{Lj} is the current that flows via inductance $j = 1, 2, 3$; I_L is the current at the converter's output; V_I is the input voltage; V_O is the converter's output voltage; D is the duty cycle.

The condition of space is expressed as follow:

$$x_1 = V_{ref} - V_O;$$

$$x_2 = \dot{x}_1 = -\frac{\mathrm{d}V_O}{\mathrm{d}t} = \frac{1}{C \cdot \left(\frac{V_O}{R} - \int \left(\frac{u \cdot V_I - V_O}{L} \right) \mathrm{d}t \right)}, \qquad (3)$$

where V_{ref} is the required output value.

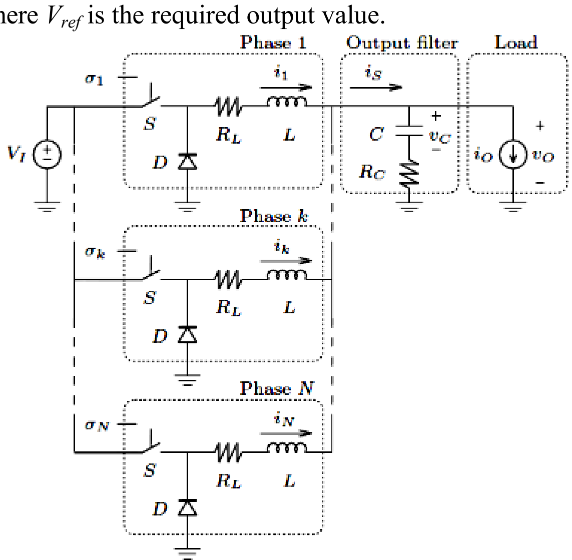

Fig. 1. Paralleled-multicellular converter

Controller design. We develop a robust control strategy in a way that our multicell buck converter become more stable, more efficient and able to cope with parametric variation.

At this level, our interest is to explore an adaptive feedback current control approach to tackle this difficulty, by using a variable-bandwidth hysteresis modulation to limit the nonlinearity phenomena in traditional sliding mode control to fix the switching frequency. The reconfiguration of the (3) helps us to design the sliding mode voltage controller:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{RC} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{V_I}{LC} \end{bmatrix} \cdot u + \begin{bmatrix} 0 \\ \frac{V_{ref}}{LC} \end{bmatrix} . \qquad (4)$$

We can determine the switching function u, by taking into account the estimated state trajectory including the control parameters x_1 and x_2. Clearly, the basic principle of sliding mode control is to design a control law that will direct the trajectory of state variables to a desired operating point. In the case of the buck converter under study, it is appropriate to have a control law that adopts a switching function such that:

$$u = \frac{1}{2 \cdot (1 + \mathrm{sign}(S))} , \qquad (5)$$

where u is the logic state of the power switch of the converter; S is the path of the instantaneous state.

The proposed control scheme shown in Fig. 2 requires that the instantaneous information on the two converter states x_1 and x_2 be fed into the controller to produce the control signal u as described in (5).

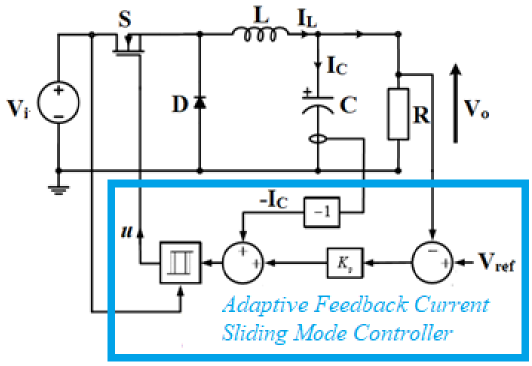

Fig. 2. Variable band-width hysteresis modulation-based sliding mode current controller

The method of implementing the sliding mode control is to use a relay of the sign function with the calculated trajectory S as shown in Fig. 3. This method is commonly used and known as the conventional strategy of the sliding mode, as illustrated in Fig. 4.

When $u = 1$, the phase trajectory for any arbitrary starting position on the phase plane will converge to the equilibrium point ($x_1 = V_{ref} - V_O$; $x_2 = 0$), after a finite time period. Similarly, when $u = 0$, all trajectories converge to the equilibrium point ($x_1 = V_{ref}$; $x_2 = 0$). Thus, the sliding surface is defined by:

$$S = K_{p1} \cdot \left(V_{ref} - V_O \right) + K_{p2} \cdot i_O ; \qquad (6)$$

$$K_{p1} = \frac{1}{r_C \cdot C} ; \quad K_{p2} = -\frac{1}{C} . \qquad (7)$$

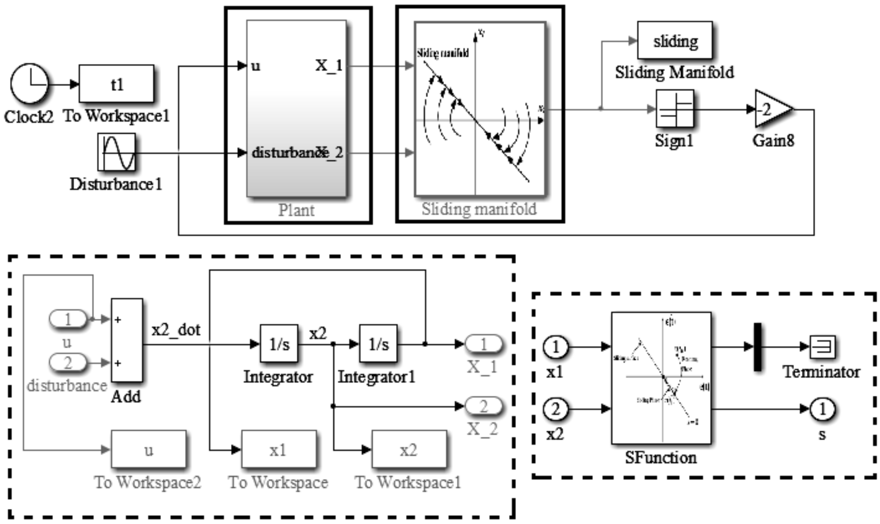

Fig. 3. Simulation of the sliding mode control in relation to the converter state variables

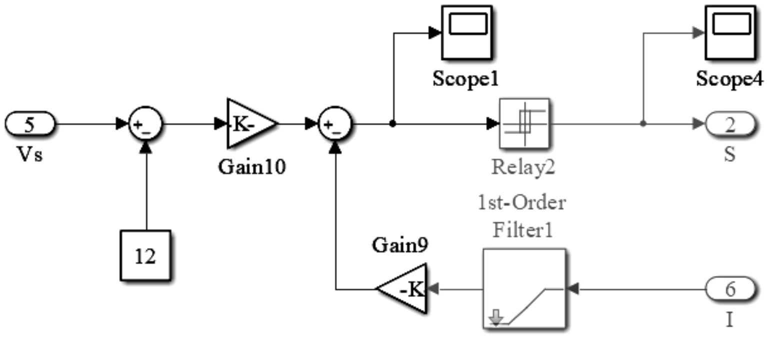

Fig. 4. Diagram of the controller in conventional sliding mode

Given this, it is simpler to reconfigure the switching function as described below:

$$S = \frac{1}{r_C \cdot \left(V_{ref} - V_O\right)} - i_O \,. \tag{8}$$

The control is applied simultaneously without phase shift to the three topologically identical cells of a non-isolated and asynchronous converter. The objective is to fix the switching frequency of the converter by referring to an adaptive feedback approach. For this purpose, we integrate a hysteresis modulator and develop a variable hysteresis band function to mitigate the non-linearity phenomenon of the conventional sliding mode. Then, we apply an adaptive feedback current control technique to overcome the dilemma of variable switching frequency. Still in order to ensure the fixed frequency operation of the proposed hysteresis modulator, a requirement is imposed, and that the hysteresis bandwidth must satisfy it, is:

$$B_{\text{var-width}} = \frac{\Delta i_O}{2} = \frac{\left(V_I - V_O\right)}{2 \cdot L \cdot fw} \cdot \left(\frac{V_O}{V_I}\right). \tag{9}$$

The converter control scheme has two modes of operation: one when the error paths are outside the boundary layer and the other when they are inside the boundary layer. The boundary layer, which varies in time, is formed by a frequency ramp signal (fw = 1/T). The boundaries of this layer correspond to the maximum and minimum values of the ramp. Figure 5 duplicates the control scheme of the variable band hysteresis model based on the sliding mode. At the beginning of each switching cycle, we determine whether the error paths are within the limits of the time-varying ramp and, based on this, we determine the operating mode.

Simulation results and stability analyses. In this section, and to properly study the behavior of the closed-loop multi-cell DC-DC buck converter and the evaluation of its performance under stable and dynamic conditions, several robustness tests have been performed to analyze the sensitivity of the implemented strategies to the variations of the converter parameters.

Figure 6 shows the response of the output voltage and the output current of the converter to parametric changes. It seems clear that the system operating with the sliding mode controller combined with a variable band hysteresis modulation obtains a better compromise from transient to steady state. Thus, its transition response is smoother, more stable, without overshoot and with less oscillations.

Figure 6,*a* shows the output voltage response and output load current response when the system undergoes a change in output reference from 8 V to 12 V. The switching from one value to another is almost similar is characterized by high precision with a relatively short transition time.

Figure 6,*b* shows that, during an increase/decrease in resistance every 0.2 s, the closed-loop output voltage response exhibits an undesirable transient drop that lasts a few seconds followed abruptly by a steady state.

Figure 6,*c* shows the output voltage response and the output load current response when the system undergoes a change in supply, every 0.2 s, it varies between 40 V and 60 V and the output voltage is regulated to 12 V. There is a slight increase in amplitude, however, the output voltage and output load current vary around the reference value.

The simulations performed show extremely encouraging results regarding the efficiency and robustness of reference tracking, the control law allows a faster rejection of the effect of load change. These results demonstrate the effectiveness of the sliding mode control for such a type of converter and mainly for a dual-battery conversion system. This finding highlights the key contribution of our work: we obtain a large reduction of the switching frequency variation thanks to the suggested technique.

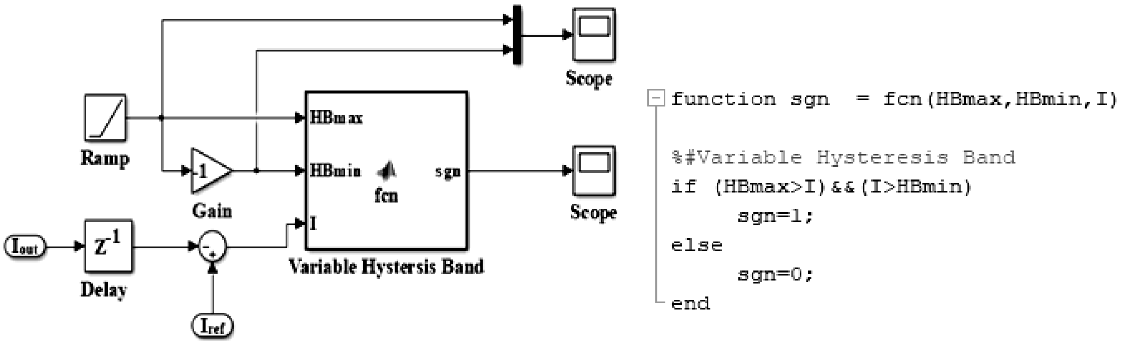

Fig. 5. The control scheme of the variable band hysteresis model based on the sliding mode

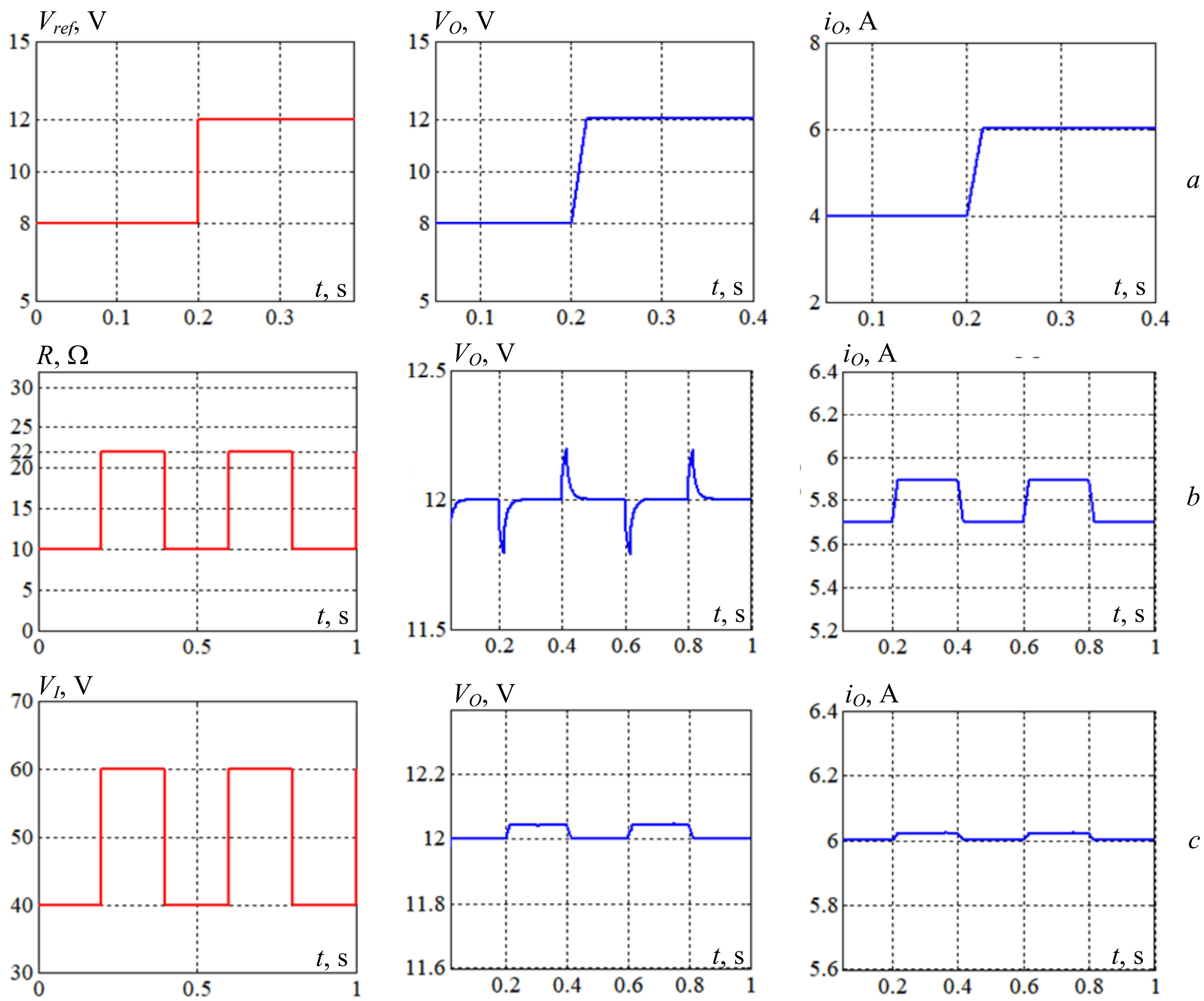

Fig. 6. Response of the output voltage V_O and output current i_O of the converter to parametric changes:
a) Variation of the reference voltage V_{ref} from 8 V to 12 V;
b) Increase/decrease of the load R from 10 Ω to 22 Ω;
c) Increase/decrease of the input voltage V_I from 40 V to 60 V

Conclusions.

It is found that the sliding mode based variable bandwidth hysteresis control is favored as it provides superior performance in both source voltage disturbance rejection and load transient response with greatly desired output voltage tracking and also provides high efficiency. This sort of control has been shown to be effective in both stability and trajectory tracking challenges. In addition, this controller is faster to the point that the response time at 5 % is mainly short. Its appropriate dynamic accuracy is characterized by zero overshoot during the transient of the output voltage response. Thus, it provided similar performance, improved dynamic drive and could adapt to varieties of voltage and load. The use of variable bandwidth hysteresis modulation and switching frequency fixing leads to large-scale dynamics and allows the reduction of the magnitude of the control action to the smallest achievable value as well as finite-time convergence. The simulations performed show very promising results in terms of reference tracking performance and robustness. They prove the relevance of the sliding mode control for this type of system. Not to mention that paralleling switching cells favors the increase of the output current, with a reduction of its oscillations compared to the oscillations of the currents of each phase.

Conflict of interest. The authors declare no conflict of interest.

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