On modeling and real-time simulation of a robust adaptive controller applied to a multichannel 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 multichannel 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 multichannel 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: multichannel converters, sliding mode control, high switching frequency, hysteresis modulation.

Conclusions. 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. The converter is designed to be used in EVs and HEVs, where energy efficiency and performance are critical. The converter is capable of handling high power densities and rapid load changes, making it suitable for use in these applications. The simulation results also show that the converter is robust to parameter variations and disturbances, which is essential for reliable operation in real-world conditions. The converter is designed to operate in continuous conduction mode, which is more efficient than discontinuous conduction mode. The converter is also designed to operate in a wide range of input and output voltages, making it suitable for use in various applications. The converter is designed to be compact and lightweight, which is essential for use in vehicles. The converter is also designed to be cost-effective, which is essential for the widespread adoption of electric vehicles. Overall, the converter is a promising solution for electric vehicles, and its performance and robustness are demonstrated through simulation studies.
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:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = -\begin{bmatrix} \frac{1}{LC} & -\frac{1}{RC} \\ 0 & \frac{V_l}{LC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ V_{ref} \end{bmatrix} u. \tag{4}$$

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:

$$u = \frac{1}{2 \left(1 + \text{sign}(S)\right)}, \tag{5}$$

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).

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 \( (x_1 = V_{ref} - V_F, x_2 = 0) \), 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:

$$S = K_{p1} (V_{ref} - V_F) + K_{p2} x_2; \tag{6}$$

$$K_{p1} = \frac{1}{r_c \cdot C}; \quad K_{p2} = \frac{-1}{C}. \tag{7}$$
Given this, it is simpler to reconfigure the switching function as described below:

$$S = \frac{1}{r_C \cdot (V_{ref} - V_O)} \cdot i_O. \quad (8)$$

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:

$$B_{\text{var-width}} = \frac{\Delta i_O}{2} \cdot \frac{(V_I - V_O)}{2 \cdot L \cdot f_w} \cdot \frac{V_I}{V_O}. \quad (9)$$

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 ($f_w = 1/T$). 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

```matlab
function sgn = fcn(HSmax, HSmin, I)
    if (HSmax > I) && (I > HSmin)
        sgn = 1;
    else
        sgn = 0;
    end
```

**Fig. 6.** The 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 $V_{in}$ 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...


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