Robust tracking controller for SEPIC drivers

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The non-minimum phase, non-linear nature of the SEPIC (single-ended primary inductor converter) makes it very difficult to get robust operating conditions under load variations. Sliding-mode control method is utilised to design a robust controller for tracking control of SEPIC converters for various applications. The implementation of the method is illustrated with the use pulse-width modulation comparators in the control loop to preclude the risk of modulator saturation and to ease the operations. The performance of the SEPIC converter is investigated through numerical simulation and analogue electronics implementation to show the validity, robustness and feasibility of the proposed controller.

Introduction: A SEPIC (single-ended primary inductor converter) driver is required in many applications including LED backlight current source, Li-ion backlight OLED and high-brightness-LED driver, LED flash driver, motor driver, handheld devices and automotive applications [1, 2]. The SEPIC has capability of providing smooth input current and can operate over a wide range of output voltage, both above and below the source voltage. On the other hand, the SEPIC is a fourth-order non-minimum phase non-linear system and its behaviour depends on operating conditions and load variations [3]. Therefore, it is difficult to design an effective controller that stabilises the converter with a satisfactory control performance for the practical applications.

The available SEPIC control techniques are based on the hysteretic and pulse-width modulation (PWM) controllers. The hysteretic controllers are based on hysteretic current-mode control [4], where the sum of the inductor currents is used as a control variable. These approaches are not robust against load variations and can result in chaotic behaviours. The fixed-frequency PWM controllers are also based on the current-mode control and can be classified as peak current-mode control [5], average current-mode control [6], non-linear carrier control [7], and one-cycle control [8]. The most significant one is the one-cycle control which is simply a pulsed non-linear method that uses constant frequency pulses to simultaneously activate or reset the transistor and the voltage feedback integrator. However, the one-cycle control method is complex and not robust during load variations.

This work proposes a robust control strategy involving integral reconstruction-based sliding-mode control for effective tracking control of SEPIC drivers. Sliding-mode control allows robust control strategies with switching modes [9], which makes it a natural tool for switch-mode power converters. An inventive integral reconstruction action is incorporated into the sliding-mode control scheme for proposing a robust controller in the presence of large load variations.

Robust control design for SEPIC drivers: SEPIC is a DC/DC-converter which provides a positive regulated output voltage varying from above to below the input voltage. Fig. 1 shows a simple circuit diagram of the SEPIC converter, consisting of coupled inductors L_1 and L_2, a coupling capacitor C_1, an output capacitor C_2, a switching transistor and a diode. In continuous conduction mode, by considering the structural topologies within a switching period, i.e. off-state with $u = 0$ and on-state with $u = 1$, the SEPIC is modelled with a fourth-order non-linear system

$$\begin{aligned} L_1\dot{I}_1 &= -(1-u)(V_1+V_2)+E \\ C_1\dot{V}_1 &= (1-u)I_1 - uI_2 \\ L_2\dot{I}_2 &= uV_1-(1-u)V_2 \\ C_2\dot{V}_2 &= (1-u)(I_1+I_2)-V_2/R \end{aligned} \tag{1}$$

where inductor currents, I_1 and I_2, and capacitance voltages, V_1 and V_2, are the state variables of system, and the control signal takes only discrete values, $u \in \{0, 1\}$. The control objective is to keep the output voltage constant during the tracking a reference voltage V_r. For a reference V_r, the equilibrium point of SEPIC is obtained from (1) as

$$I_1^* = V_r^2/RE, \quad V_1^* = E, \quad I_2^* = V_r/R, \quad u^* = V_r/(E+V_r) \tag{2}$$

where u^* is the average control value during the steady state. Since SEPIC is a fourth-order non-minimum phase non-linear system, non-linear control strategies are more suitable to control design, but they must provide a good system performance and simplicity to facilitate implementations. The computation time also must be less than the switching period.

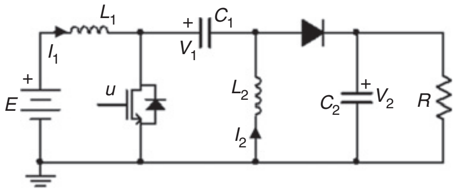

Fig. 1 *Practical SEPIC circuit diagram*

Since the dynamic models of the converters are described by differential equations with discontinuous right-hand sides due to their state dependent discrete input signals, sliding modes can be induced over appropriate state-dependent surfaces in such systems. The sliding-mode control has a simple implementation advantage over other control methods. Now, for the SEPIC dynamics given in (1) and its equilibrium point (2), a switching surface is proposed as

$$\sigma = -I_1 + \delta\int_0^t \left[V_r - V_2(\tau)\right]\mathrm{d}\tau \tag{3}$$

where δ is a positive valued control parameter to be designed. Then the corresponding average control signal can be found when $\dot{\sigma} = 0$ as

$$u_{av} = 1 - \left[E - L_1\delta(V_r - V_2)\right]/[V_1 + V_2] \tag{4}$$

The average control under non-saturated operating conditions ensures

$$0 < u_{av} < 1 \tag{5}$$

with $V_1 + V_2 - E + L_1\delta(V_r - V_2) > 0$ and $E - L_1\delta(V_r - V_2) > 0$. These conditions can also be used to determine a value for the control parameter δ, i.e.

$$0 < \delta < E/L_1V_r \tag{6}$$

Under the average control, the ideal sliding dynamics (zero dynamics) corresponding to the sliding condition, $\sigma = \dot{\sigma} = 0$, can be given by

$$\begin{aligned} L_1\dot{I}_1 &= L_1\delta(V_r - V_2) \\ C_1\dot{V}_1 &= \frac{E - L_1\delta(V_r - V_2)}{V_1+V_2}I_1 + \left[\frac{E - L_1\delta(V_r - V_2)}{V_1+V_2} - 1\right]I_2 \\ L_2\dot{I}_2 &= \left[1 - \frac{E - L_1\delta(V_r - V_2)}{V_1+V_2}\right]V_1 - \frac{E - L_1\delta(V_r - V_2)}{V_1+V_2}V_2 \\ C_2\dot{V}_2 &= \frac{E - L_1\delta(V_r - V_2)}{V_1+V_2}(I_1+I_2) - \frac{1}{R}V_2 \end{aligned} \tag{7}$$

The stability of the ideal sliding dynamics can be analysed via linearising the system around the equilibrium point. The eigenvalues of the linearised sliding dynamics can be calculated from $\det(\lambda I - A) = 0$, and it can be shown that as long as the condition (6) is satisfied, the ideal sliding dynamics for the given equilibrium point is asymptotically stable. Therefore, the proposed sliding surface is suitable to accomplish the stabilisation of the SEPIC system with the discrete controller

$$u = \begin{cases} 1 & \text{if } \sigma > 0 \\ 0 & \text{if } \sigma < 0 \end{cases} \tag{8}$$

The stability of the system under the proposed controller can be evaluated through Lyapunov stability, i.e. for $V = \sigma^2/2 > 0$, stability is ensured if its time derivative is negative definite, $\sigma\dot{\sigma} < 0$. From (3), for a constant reference, V_r, the time derivative of the switching surface can be written as

$$\dot{\sigma} = \delta(V_r - V_2) + [(1-u)(V_1+V_2) - E]/L_1 \tag{9}$$

From (8), if $\sigma > 0$, then $\dot{\sigma} = \delta(V_r - V_2) - E/L_1 < 0$ and $\sigma\dot{\sigma} < 0$. If $\sigma < 0$ and $u = 0$, then $\dot{\sigma} = [(V_1 + V_2) - E]/L_1 + \delta(V_r - V_2) > 0$ [due to the condition given in (5)] and $\sigma\dot{\sigma} < 0$, so the system has stable dynamics. Consequently, the proposed control strategy ensures that the system trajectory will reach the switching surface and stay on the surface thereafter.

Results: The tracking performance of the proposed control method is first illustrated with numerical simulations as shown in Fig. 2. The converter parameters with parasitic resistances are taken as $L_1 = L_2 =$ 100 µH, $C_1 = C_2 = 100$ µF, $r_{L_1} = r_{L_2} = 20\,\mathrm{m\Omega}$, $r_{C_1} = r_{C_2} = 10\,\mathrm{m\Omega}$, $E = 15$, $r_{\mathrm{on}} = 1\,\mathrm{m\Omega}$ and $R = 50\,\Omega$. Fig. 2*a* displays the step voltage response of the control method when V_r varies between 8 and 25 V. The control parameter is selected based on the largest voltage reference as $\delta = 20$ to satisfy condition (6). The SEPIC output voltage, V_2, follows the step references with zero steady-state error. Fig. 2*b* displays the SEPIC inductor currents staying on their equilibrium points. Fig. 2*c* displays the control signal and its average. The proposed controller has a highly satisfactory transient response and zero steady-state error.

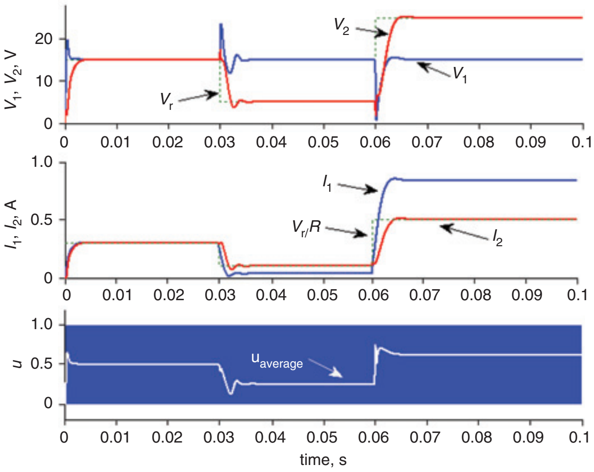

Fig. 2 *Numerical simulation results. Tracking performance of proposed controller for step variations*

a Output voltage V_2
b Input current I_1 and output current I_2
c Control signal u and its average value

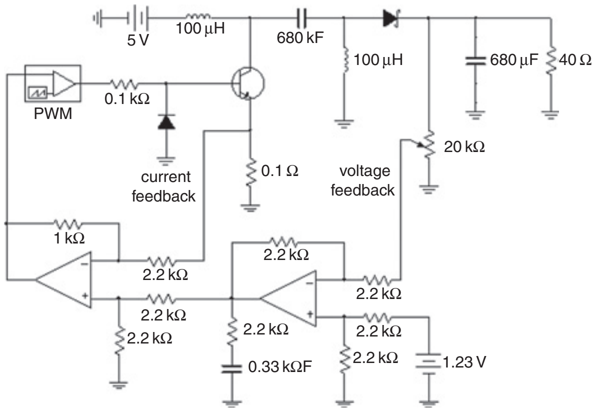

Fig. 3 *Simple circuit realisation of proposed controller*

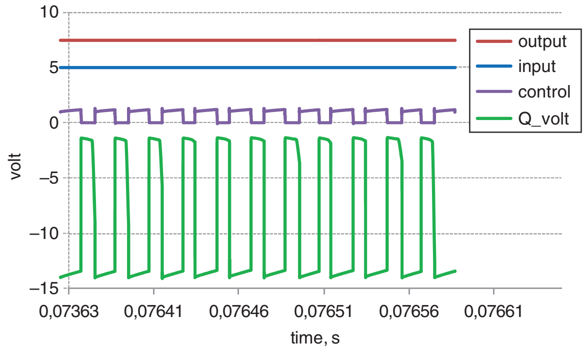

Fig. 4 *Circuit implementation results showing input E, output V_2, control command u and switch voltage*

The controller is also implemented with the analogue electronics as given in Fig. 3. The feedback voltage and current are measured through sensing resistors. The controller is realised with the pulse width modulator for simplicity and practical reasons. Circuit implementation results are shown in Fig. 4. The output voltage is adjusted by using a potentiometer to get desired results. The controller changes the duty cycle of the PWM driver to adjust converter output. The control signal and switch pin voltage variations, working in a complementary style, are also seen in the figure. The controller provides highly smooth (small ripple) regulated output voltage.

Conclusion: A robust sliding-mode based controller for SEPIC converters is proposed. The converter has been controlled through the input inductor current and load voltage. The control law is designed based on integral reconstruction and sliding-mode control theory. The proposed controller has a simple, fast dynamic response, only one control parameter needed to be selected, and ensure insensitivity to load parameter variations with inherent current limitation. The circuit realisation results are in good agreement with the theoretical predictions and validate highly satisfactory and robust control performances.

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One or more of the Figures in this Letter are available in colour online.

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