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Hysteresis and Delta Modulation Control of Converters Using Sensorless Current Mode

Jonathan W. Kimball, *Senior Member, IEEE*, Philip T. Krein, *Fellow, IEEE*, and Yongxiang Chen

Abstract—**Sensorless current mode (SCM) is a control formulation for dc–dc converters that results in voltage-source characteristics, excellent open-loop tracking, and near-ideal source rejection. Hysteresis and delta modulation are well-known, easy-to-construct large-signal methods for switched systems. Combining either large-signal method with SCM creates a controller that is simpler and more robust than a pulse-width modulation (PWM) based controller. The small-signal advantages of PWM-based SCM are retained and expanded to include converter response to large-signal disturbances. These approaches can be used with any converter topology over a broad range of operating conditions. In the present work, hysteresis and delta modulation SCM controllers are derived and simulated. Extensive experimental results demonstrate the large-signal behavior of both control schemes.**

Index Terms—**Discontinuous conduction mode (DCM), hysteresis, delta modulation, sensorless current mode (SCM).**

I. INTRODUCTION

SENSORLESS current mode (SCM) control was demonstrated in the early 1990's [1] as an alternative to conventional voltage-mode (VM) and current-mode (CM) dc–dc converter techniques, with a simpler structure than CM and better performance than VM. An open-loop SCM-controlled converter has perfect line regulation, and output impedance determined entirely by the circuit components [2]–[7]. Digital implementations are possible [8]. The SCM control law relies on the integral of the inductor voltage combined with a reference voltage value. SCM implementations have been augmented with average current sensing [1] for sharing and protection, a technique that has reappeared as "lossless" current sensing [9], [10]. A low-pass filter may be used in place of the SCM integrator to mimic lossless current sensing, but in most cases, using a modest feedback system with standard SCM yields significantly better controller performance.

This letter considers implementations of SCM controls in hysteresis and delta modulation modes. Hysteresis SCM control was introduced in [2] and is appealing for its inherent simplicity, its immunity to flux creep in coupled converter topologies, and its wide dynamic range. Delta modulation approaches similarly yield simple implementations, including the possibility for an all-digital controller.
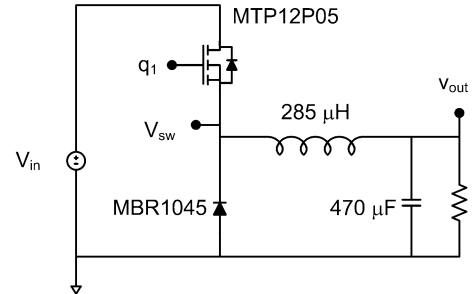
Fig. 1. Buck converter with relevant signals.

II. REVIEW OF SCM CONTROL PROCESS AND FIXED-FREQUENCY IMPLEMENTATION

Consider an inductor in a buck converter (Fig. 1). For ideal parts, given a switching function q_1 for the controlled switch, the inductor current is

$$i_L = \frac{1}{L} \int v_L dt = \frac{1}{L} \int (q_1 V_{\text{in}} - v_{\text{out}}) dt. \qquad (1)$$

The SCM control law results from replacing v_{out} with a reference level V_{ref}. The resulting current estimate

$$v_I = K \int (q_1 V_{\text{in}} - V_{\text{ref}}) dt \qquad (2)$$

is used in a conventional PWM process to determine switch operation. The gain K is chosen to give appropriate dynamic response and need not match $1/L$. For a more precise closed-loop version, V_{ref} is replaced by a function of the desired output voltage V_{ref}^* and measured v_{out}. Even in the open-loop control version, v_{out} is forced to V_{ref}. This control law is similar to that of one-cycle control [11] except that no integrator reset is used. However, the SCM approach extends to all topologies, and control laws can be constructed based on an inductor voltage [4] or a capacitor current. The control law (2) is effectively a flux observer [4]. In an inductor, flux and current are proportional, but in transformers and coupled inductors, flux is not linked to a unique current. SCM control has been used effectively in forward converters and other topologies to ensure that a transformer or coupled inductor operates at the proper flux level [2]. SCM is related to previous approaches [12], [13] in which the voltage on an auxiliary winding is integrated to form an observer for the flux in the core. By contrast, SCM uses desired inductor voltage in an observer as part of the control loop. The integrator inherent to estimating flux drives the actual inductor voltage to the desired value. The SCM process works in both continuous and discontinuous conduction modes, as discussed below, with a simple two-terminal inductor.
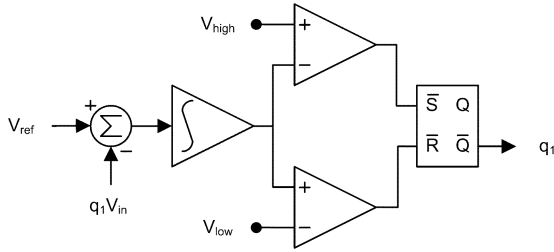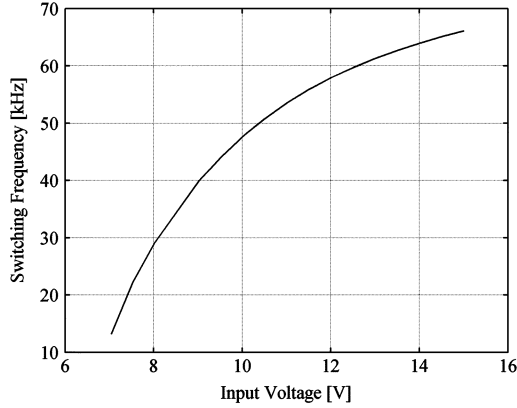
Fig. 2. Hysteresis SCM controller.

Fig. 4. Ripple current variation with input voltage.

Fig. 3. Frequency variation with input voltage.

Fig. 5. Input voltage (top, 10 V/div), output voltage (middle, 100 mV/div, ac coupled), and inductor current (bottom, 1 A/div) through input transients (1 ms/div).

In a typical implementation, the modulation process follows from conventional CM control. A latch, with output q_1, is periodically set by a clock. The clock synchronizes a ramp, which is compared to v_I. The result of the comparison resets the latch. Previous work [7] has determined optimum ramp slope and K to null the audiosusceptibility. This modulation process yields voltage-source output characteristics, in contrast to the current-source behavior inherent in CM approaches [6].

III. HYSTERESIS AND DELTA MODULATION CONTROLS

A. Hysteresis SCM Control

The hysteresis process shown in Fig. 2 can be used instead of conventional PWM. When v_I, the output of the integrator shown, hits an upper limit, the active switch is turned off. When v_I hits a lower limit, the switch is turned on. The complete system is implemented with an integrator, two comparators, and a latch. To simplify the circuit, a Schmitt trigger can be used in place of the comparators and latch. In the development below, hysteresis SCM has been experimentally verified on a buck converter with rated output of 5 V at 3 A and rated input ranging 7 to 15 V. The inductance is 285 μH and the output capacitance is 660 μF. The controller was implemented with TL082 operational amplifiers, LM393 comparators, and a latch built from two gates of an SN74HC02. Because of the relatively low voltages, V_{sw} and V_{out} can be sensed with simple differential amplifier circuits built around the TL082 ICs. Input voltage and inductor current are not sensed. Full schematic is provided [14].
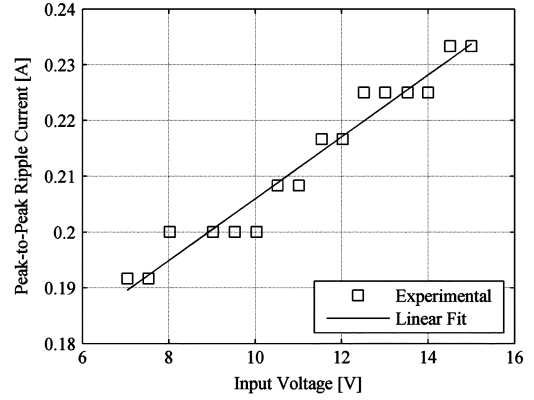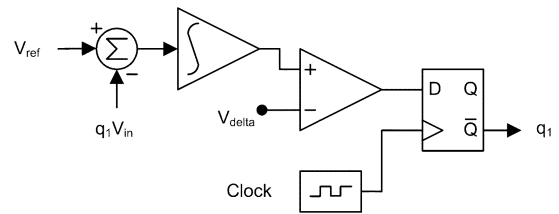

Fig. 6. SCM delta modulator.

The effective switching frequency, f_{eff}, is determined solely by the voltages involved and the width of the hysteresis band, Δv, and is given by

$$f_{eff}(V_{in}) = \frac{K \, V_{ref}(V_{in} - V_{ref})}{V_{in} \, \Delta v}. \tag{3}$$

This frequency increases monotonically with input voltage, as shown in Fig. 3 for the converter described above, with K and Δv adjusted for $f_{eff}(12.5 \text{ V}) \approx 60$ kHz. Nearly constant current ripple results, as shown in Fig. 4. The hysteresis process is effective over a broad range of operating conditions and makes effective use of the inductor.

Fig. 7. Command (top, 5 V/div) and current ripple (bottom, 0.1 A/div) with delta modulation (50 μs/div). (a) $V_{\text{in}} = 10$ V, (b) $V_{\text{in}} = 12$ V, (c) $V_{\text{in}} = 15$ V.

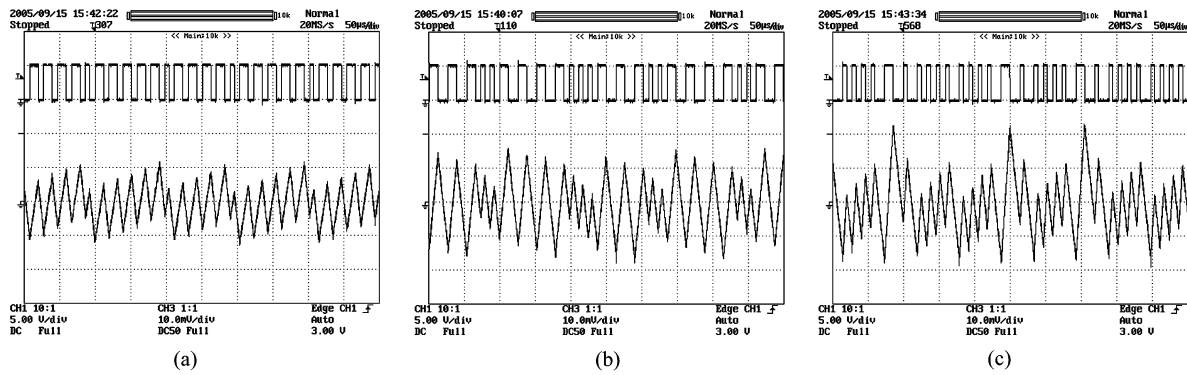Hysteresis SCM control rejects input disturbances extremely well. The slope of v_I changes with V_{in} such that higher V_{in} terminates each switching pulse earlier. The same volt-seconds are applied to the inductor before and after a step change, so there is little or no net change in inductor current. This characteristic is similar to hysteresis current control [15]. The response of the experimental converter to an input voltage wave is shown in Fig. 5. The near-square-wave input voltage was created by switching between two sources that were approximately 40% different with MOSFETs. The output is set to 5 V, so the peak disturbance of 15 mV corresponds to 0.3%. While PWM implementations of SCM are only guaranteed to reject small-signal line disturbances, hysteresis SCM, in addition, rejects large-signal line disturbances. This can be a critical advantage in systems operating from a soft source, such as a fuel cell, or from sources with significant inherent ripple, such as classical rectifiers.

B. SCM Control Based on Delta Modulation

In the delta modulation implementation of SCM, v_I is compared to a fixed level, but the comparison is sampled periodically as shown in Fig. 6. While v_I remains near the fixed level, excursions are not controlled. The use of sampling limits the switching frequency to half of the clock frequency. If a high sampling frequency is used, v_I stays nearly constant but the switching frequency is high. If a low sampling frequency is used to reduce switching losses, v_I excursions become pronounced and result in more pronounced subharmonics. All delta modulators exhibit subharmonics, as discussed in [16], [17]. A delta modulation controller was applied to the 5-V, 3-A buck converter described above. Fig. 7 clearly shows the presence of subharmonics and the nonlinear effect of input voltage. Although the sampling frequency was set at 150 kHz, the inductor generated audible noise related to the subharmonics.

For many applications, subharmonics and their negative effects are not relevant. For example, in an intermediate bus architecture, the distribution bus should be roughly regulated but all loads are served by other power converters that provide well-regulated, clean voltage. The primary advantage of delta modulation for undemanding applications is simplicity: the circuit uses an integrator, a comparator, a D flip-flop, and a clock. All-digital implementations are straightforward. The controller that was applied to the 5-V, 3-A converter was implemented with a TL082, an LM393, an SN74LS74, and an LM555. An integrated control IC could be constructed from building blocks in
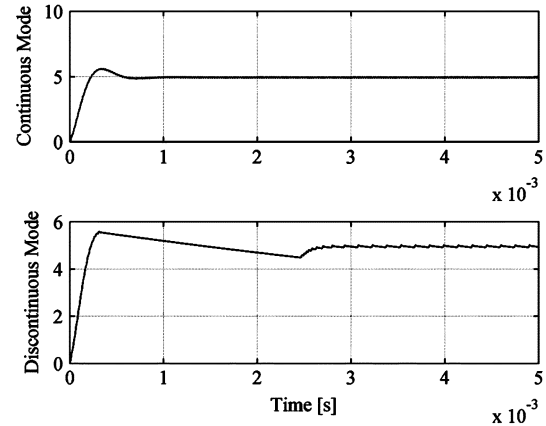

Fig. 8. Simulated startup waveforms, comparing continuous-mode operation to discontinuous mode.

a typical CM control IC. The result would be a simple, robust controller with reasonable regulation for low-end applications.

C. Discontinuous Conduction Mode

The design of a hysteresis or delta modulation control scheme must ensure that switching occurs regularly, which for SCM equates to making the integrand of (2) non-zero. Otherwise, once the switch turns off, it may never turn back on. Lockup can be avoided if the measured V_{sw} value in Fig. 1 is used in place of $q_1 V_{\text{in}}$ in (2), an approach that usually makes the circuit simpler. When the system enters discontinuous conduction mode (DCM), no current is flowing in the inductor and $V_{\text{sw}} = v_{\text{out}}$. In an open-loop converter, the average of v_{out} is less than V_{ref} because of losses in the passive elements. Therefore the integrand in (2) is always negative, so v_I will eventually cross the lower hysteresis bound or the delta modulation reference level and switching will resume.

A simulation of the above described buck converter was constructed in Dymola to explore the effect of changing loads. Dymola [18] is a generic time-domain simulation environment built on Modelica [19], an object-oriented physical modeling language. The results shown in Fig. 8 compare continuous conduction mode (CCM) and DCM for a hysteresis SCM controller. The startup peaks are approximately the same, but the recovery characteristics differ. Also, the ripple in DCM is significantly greater than in CCM due to a lower effective switching frequency. Through a simple modification of the
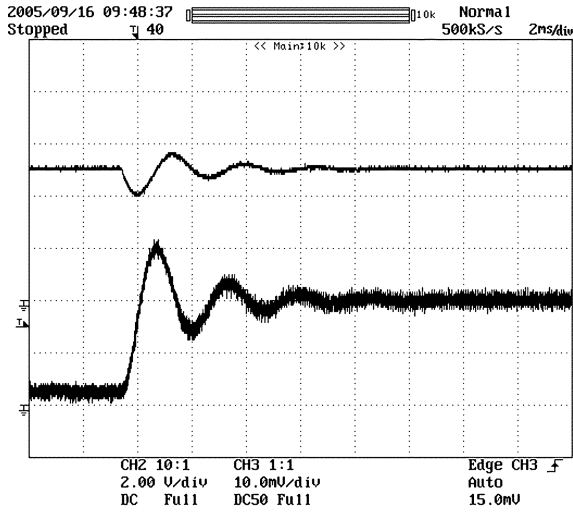
Fig. 9. Closed-loop buck converter with delta modulation SCM: v_{out} (Top, 2 V/div) and inductor current (Bottom, 2 A/div), step load transient (2 ms/div).

control law, operation of variable-frequency SCM extends into DCM, where the switching characteristics change with load in a potentially beneficial manner.

IV. CLOSING THE LOOP

The results of Section III relate to open-loop SCM control, which can be used when precise load regulation is not necessary. Precise regulation and reasonable response time can be achieved with a straightforward closed-loop system. Given some V_{ref}^* to be tracked, a feedback control such as a proportional-integral (PI) control law can be applied to yield

$$V_{\mathrm{ref}} = K_p(V_{\mathrm{ref}}^* - v_{\mathrm{out}}) + K_i \int (V_{\mathrm{ref}}^* - v_{\mathrm{out}})dt. \quad (4)$$

More sophisticated control approaches exist as well, such as including V_{ref}^* as a feedforward term. The converter will have (low) output impedance determined by the passive components, but modified by the feedback. For a buck converter, the output impedance is a damped second-order response for which series resistance has no steady-state effect once the loop is closed.

The 5-V, 3-A converter described above was controlled with delta modulation, using closed loop parameters of $K_p = 0$ and $K_i = 1000$. The response to a step load disturbance is shown in Fig. 9. Previous modeling [3], [5] was based on small-signal and fixed-frequency assumptions, so more work is needed to derive large-signal, variable-frequency models for controller design.

Can a closed-loop hysteresis SCM or delta modulation SCM controller "lock up" in DCM? The situation is more complicated than the open-loop case, as V_{ref} is now a function of v_{out}. Suppose the switches all turn off at $t = 0, v_{\mathrm{out}}(0) = V_{\mathrm{ref}}^*$, V_{ref} is given by (4) and the output load is resistive. Then

$$v_{\mathrm{out}} = V_{\mathrm{sw}} = V_{\mathrm{ref}}^* e^{-t/RC}$$
$$V_{\mathrm{ref}} = V_{\mathrm{ref}}(0) + K_p V_{\mathrm{ref}}^*(1 - e^{-t/RC})$$
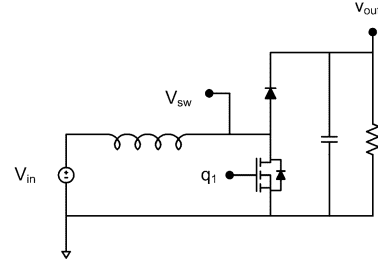$$+ K_i V_{\mathrm{ref}}^*(t - RCe^{-t/RC}). \quad (5)$$

Fig. 10. Boost converter with relevant signals.

The integrand of (2) includes three terms

$$-V_{\mathrm{ref}}(0) \quad (6)$$
$$-K_p V_{\mathrm{ref}}^*(1 - e^{-t/RC}) \quad (7)$$
$$-K_i V_{\mathrm{ref}}^*(t - RCe^{-t/RC}). \quad (8)$$

The terms given by (6) and (7) are always negative. The term given by (8) becomes negative after $t = 0.567RC$. Thus the total integrand either begins negative or becomes negative after less than one time constant and drives v_I to the lower hysteresis bound, at which time switching resumes. So a closed-loop SCM converter with any modulation strategy will never stop switching and will always drive the output to the target voltage.

V. OTHER CONVERTER TOPOLOGIES

The derivation of the SCM control law of (2) relies on the converter topology and has been shown for a buck converter. For other topologies, the approach is to write an expression for the inductor voltage and replace v_{out} with V_{ref}. Since the inductor is connected to the output through a diode in a boost, buck-boost, or flyback converter, special attention to DCM is required.

The SCM control law for the boost converter of Fig. 10 is

$$v_I = K \int (V_{\mathrm{in}} - q_2 V_{\mathrm{ref}})dt \quad (9)$$

where q_2 is unity when the diode is conducting. When implemented directly, this control law works well for CCM, in which case $q_2 = \bar{q}_1$. If the current becomes discontinuous, the control law (9) no longer appropriately observes the flux or controls the output voltage. A reasonable solution is to use

$$v_I = K \int (V_{\mathrm{in}} - q_2 V_{\mathrm{ref}} - (1 - q_1 - q_2)V_{\mathrm{sw}})dt. \quad (10)$$

The V_{sw} term will effectively set the integrand to zero to represent the zero voltage applied to the inductor when the current is discontinuous. Unfortunately, such an approach does not work with hysteresis or delta modulation, since when the integrand goes to zero, switching never resumes.

SCM can be applied to any converter topology, even in DCM, by modifying the control law to include output voltage sensing. The appropriate SCM control law for a boost converter is

$$v_I = K \int (V_{\mathrm{in}} - \bar{q}_1 V_{\mathrm{ref}})dt. \quad (11)$$
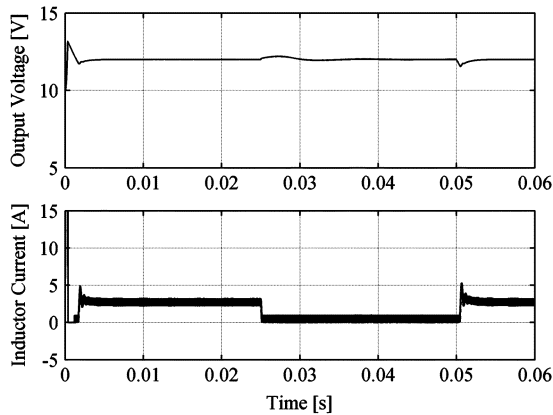
Fig. 11.   Simulated boost converter with proposed closed-loop control scheme, showing CCM and DCM.

In general, (11) is easier to implement than (9) or (10) because q_1 is known but q_2 must be sensed. During CCM, both versions are equivalent. When entering DCM, (11) will continue to generate gate commands as if the current were continuous. With no other circuitry, the output voltage would increase without bound. The solution is to use feedback. If V_{ref} is the output of a controller with integral feedback, in steady state

$$\langle \bar{q}_1 V_{\mathrm{ref}} \rangle = \langle q_2 V_{\mathrm{ref}}^* \rangle = \langle q_2 V_{\mathrm{out}} \rangle. \tag{12}$$

The system is stable in CCM or DCM. Fig. 11 shows simulation results for a boost converter with the same parameters as the experimental buck converter and $V_{\mathrm{ref}}^* = 12$ V.

Another option is to add a hysteretic supervisor. When the output voltage exceeds some $V_{\mathrm{th,hi}}$, switching is disabled but the SCM circuitry continues to generate switching signals in accordance with (11). When the output voltage decreases below $V_{\mathrm{th,lo}}$, switching is re-enabled. The output voltage remains bounded, though it does not converge asymptotically as in the continuous feedback case.

Either continuous or hysteretic feedback can be applied to a buck-boost or flyback converter with the control law given by

$$v_I = K \int (q_1 V_{\mathrm{in}} - n\bar{q}_1 V_{\mathrm{ref}})\,dt \tag{13}$$

where n is the turns ratio of a flyback converter. For a nonisolated buck-boost converter, $n = 1$. An SCM control law that never allows the integrand to vanish can be defined for any topology, so hysteresis or delta modulation can always be used.

VI. Conclusion

SCM control has been implemented in both hysteresis and in delta modulation frameworks. Implementation circuits are simpler than for fixed-frequency PWM and are robust over varying operating conditions. The underlying advantages of SCM over conventional techniques are retained. Near-ideal

line regulation (null audiosusceptibility) is expanded from the small-signal conditions of fixed-frequency PWM to large-signal disturbances by the use of these large-signal techniques. While load regulation of an open-loop converter is dictated by the natural dynamics of the converter, closed-loop control can be used to improve steady-state tracking. Any topology can benefit from closed-loop SCM, which was shown for both buck and boost converters. Extensive experimental results, augmented with simulations, demonstrated both hysteresis SCM and delta modulation SCM in a variety of operating conditions and verified the large-signal characteristics described.

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