REPLY

GENERIC SPICE COMPATIBLE MODEL OF CURRENT FEEDBACK IN SWITCH MODE CONVERTORS

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The mechanism of duty cycle generation in current mode (CM) and average current mode (ACM) PWM convertors is examined and found to be identical except for the functional relationship of the controlling parameters. This result is used to develop a SPICE compatible and topology independent generic current mode (GCM) model.

Introduction: Current mode (CM) [1] and average current mode (ACM) [2, 3] control were shown to be useful design techniques for improving the dynamic response of PWM convertors. The purpose of the present study was to develop a unified SPICE [4, 5] compatible model of PWM convertors with current feedback, for which the CM and ACM realisations are private cases.

Generic current mode model: Examination of the fundamental features of CM realisation and ACM realisation (Fig. 1) reveals that they only differ in the frequency response of the current feedback loop. In the CM this response is approximately frequency independent (k_1 in Fig. 1). In ACM, the response is shaped by the Z_1 and Z_2 networks of the feedback amplifier A_1 (Fig. 1*b*). It has been proposed [2] that this response should include a flat portion around the switching frequency to retain the triangular shape of the inductor current. It will be assumed in the following, therefore, that the output signal of amplifier A_1 includes a remnant of the inductor current triangular waveform (except for possible curvature of the corners) multiplied by a constant (k_1).

In CM realisation (Fig. 2), the output of the error amplifier V_c, modified by a 'compensation slope' M_c [1] is compared to the inductor current I_L having a rising slope k_1m_1, a falling slope k_1m_2 and low frequency component A. The average

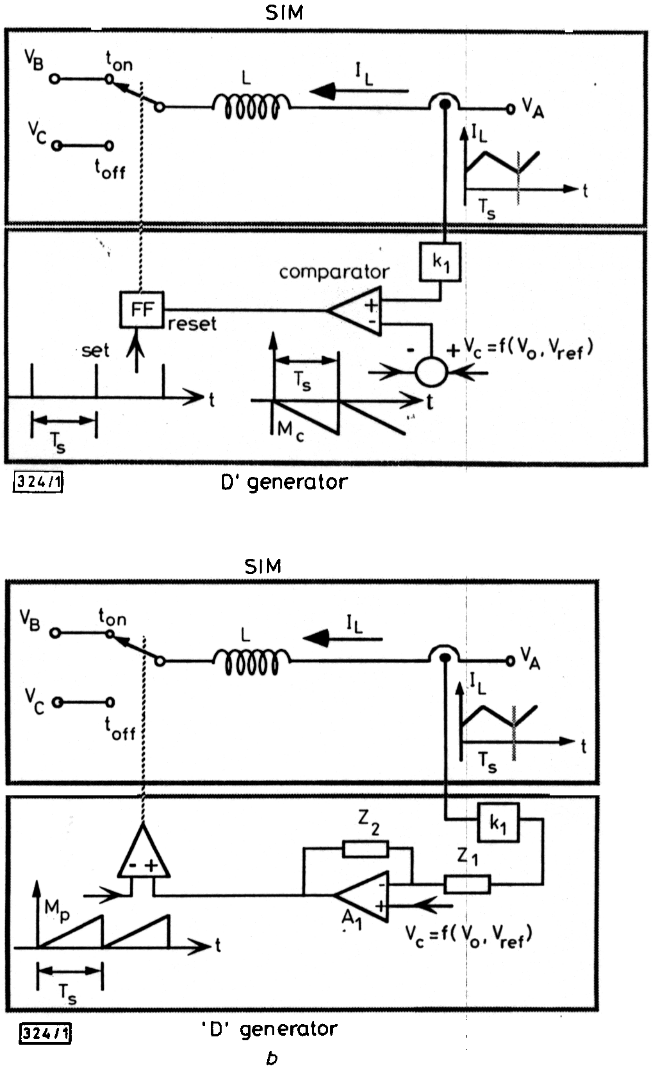

Fig. 1 *Generic features of current mode (CM) and average current mode (ACM) PWM convertors*
a CM
b ACM

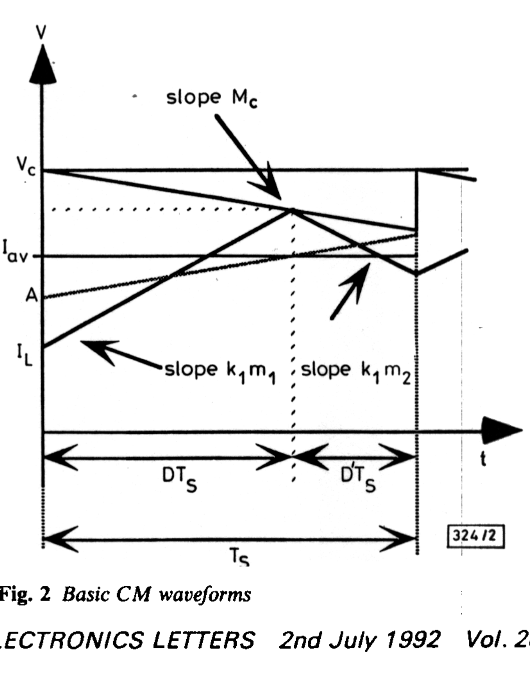

Fig. 2 *Basic CM waveforms*

magnitude of A, per cycle, is denoted I_{av}. The PWM switch is turned 'off' when the amplified inductor current reaches the momentary value of V_c.

In ACM (Fig. 3), the switch is turned 'off' when the magnitude of the sawtooth rising slope S_c reaches the output voltage of amplifier A_1. The output of this amplifier V_A includes a

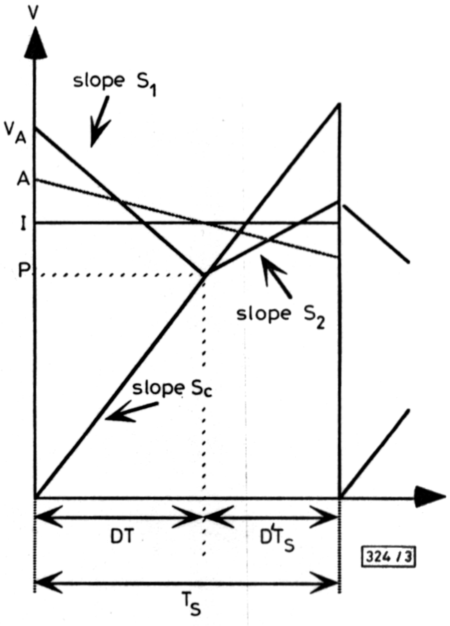

Fig. 3 *Basic ACM waveforms*

remnant of the inductor current waveform with slopes S_1 and S_2 and a low frequency component A which is a function of the inductor current and output voltage. The average value of A, per cycle, is denoted I.

Considering the similarity of duty cycle D generation in the two cases, it is conceivable that a generic current mode (GCM) model can be used to describe both of them, as well as many other possible realisations.

Duty cycle function of GCM model: The basic duty cycle D function of the GCM is a function of the switching period, the closing slopes S_c and S_1 and the per cycle average I of the signal which comprises a falling slope S_1 and a rising slope S_2. The intersection at DT_s determines the duty cycle. Defining P as the magnitude of the rising slope S_c at the intersection time DT_s we find

$$P = S_c DT_s \tag{1}$$

The distance $(I - P)$ in Fig. 3 is the average value of the two triangles formed by slopes S_1 and S_2:

$$I - P = \frac{\dfrac{(S_1 DT_s)DT_s}{2} + \dfrac{(S_2 D'T_s)D'T_s}{2}}{T_s} \tag{2}$$

where $D' = 1 - D$ and the slopes S_1 and S_2 are taken in absolute value. By combining eqns. 1 and 2 we obtain [8]

$$I = S_c DT_s + 0{\cdot}5 S_1 D^2 T_s + 0{\cdot}5 S_2 (D')^2 T_s \tag{3}$$

ACM case: In the private case of ACM, the low frequency signal fed to the comparator is

$$I_{ACM} = F_c V_c - \bar{I}_L k_1 F_I \tag{4}$$

where k_1 is the gain of the current loop at f_s, $\bar{I}_L$ is the average inductor current, V_c is the voltage feedback signal and F_I and F_c are the transfer functions of the current and voltage paths:

$$F_I = \frac{Z_2}{Z_1} \tag{5}$$

$$F_c = \frac{Z_1 + Z_2}{Z_1} = \;\; + F_I \tag{6}$$

The slopes of the ACM are defined as follows:

$$S_1 = F_I k_1 m_1 \tag{7}$$

$$S_2 = F_I k_1 m_2 \tag{8}$$

$$m_1 = \left| \frac{V_A - V_B}{L} \right| \tag{9}$$

$$m_2 = \left| \frac{V_A - V_C}{L} \right| \tag{10}$$

$$S_c = M_p \tag{11}$$

where V_A and V_B are the switched inductor voltages as defined in Fig. 1*b*, L is the inductance of the main inductor and M_p is the slope of the PWM slope (Fig. 1*b*).

CM case: In this case, the low frequency component of the signal fed to the comparator is

$$I_{CM} = F_c V_c - \bar{I}_L k_1 F_I \tag{12}$$

$$S_1 = F_I k_1 m_1 \tag{13}$$

$$S_2 = F_I k_1 m_2 \tag{14}$$

However

$$F_c = F_I = 1$$

and

$$S_c = M_c \tag{16}$$

where M_c is the compensation slope (Figs. 1*a* and 2).

Results and conclusions: Following the simulation procedure suggested earlier [4, 6, 7], a SPICE compatible equivalent circuit of the generalised power stage which includes the switched inductor model (SIM) [6] and the GCM, was developed (Fig. 4). Simulations were carried out by HSPICE (Meta

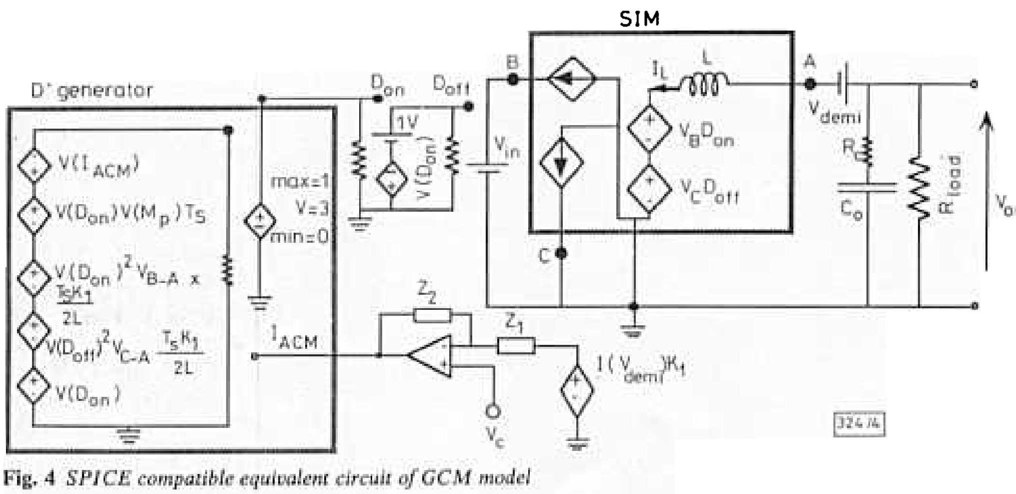

Fig. 4 *SPICE compatible equivalent circuit of GCM model*

Software Inc., Campbel, CA, USA) on a VAX (Digital Equipment Corp., Marlboro, Mass.) computer and were found to be in good agreement with published experimental results [3].

Important conclusions of the present study are that the CM and ACM are private cases of a generic current feedback family and that both may be subjected to subharmonic oscillations [1].

The ability to carry out both small and large signal simulations without the need for any further mathematical derivations could make the proposed topology-independent models a viable research and engineering tool.

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