(54) Title: ADAPTATIVE SLOPE COMPENSATOR FOR CURRENT MODE POWER CONVERTER

(57) Abstract

An adaptive slope compensator is disclosed which is used for compensating the current loop (200) and improving the circuit performance of a current mode power converter. The slope compensator is modulated by a voltage feedback loop signal (VFB) of the power converter. The slope compensation signal can thus automatically be adjusted to optimize its operating parameters. Furthermore, by synchronizing with the switching signal (VSW) of the power converter, the slope compensation signal is reset to zero in response to the OFF switch of the switching signal, thereby eliminating the oscillation problem of no load operation encountered by prior slope compensation designs.
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ADAPTIVE SLOPE COMPENSATOR FOR CURRENT MODE POWER CONVERTER

Field of the Invention

This invention relates to the power converters and more specifically to current mode power converters.

Background of the Invention

Various power converters are available for transforming an unregulated input voltage to a regulated output voltage with a specific magnitude. The technologies of power conversion such as forward and flyback are well described as the prior art. Although the advantages of current mode control over voltage mode control have been amply demonstrated, the slope compensation has to be added in the current loop to solve the instability problems. Many texts can explain the operation of current mode and the slope compensation, such as (a) Keith H. Billings "Switchmode Power Supply Handbook," McGraw-Hill Book Co., p.3.148-p.3.150; (b) Abraham I. Pressman "Switching Power Supply Design", McGraw-Hill Book Co., p.105-p.136; p.143-p.165; (c) "Modelling, Analysis and Compensation of the Current-Mode Converter," Unitrode Corp., Application Note U-97; and (d) "Practical Considerations in Current Mode Power Supplies," Unitrode Corp., Application Note U-111. However, there still exist several drawbacks in conventional slope compensation technologies. Thus, in order to solve these problems and improve performance, mathematical analysis and practical circuit tests have been performed to establish the fundamentals of this invention. The characteristic analysis of conventional slope compensation are listed as follows:
(A) Advantage I: Slope compensation stabilize the current loop

A general circuit of current mode power converter is shown in Fig. 1, its symbols defined are:

- **Pwr**: power converter
- **T_M**: power transformer
- **N_p**: primary turn ratio of T_M
- **N_s**: secondary turn ratio of T_M
- **L_p**: primary inductance of T_M
- **L_s**: secondary inductance of T_M
- **I_p**: primary current of T_M
- **I_pp**: primary peak current of T_M
- **I_pa**: primary average current of T_M
- **I_s**: secondary current of T_M
- **I_sp**: secondary peak current of T_M
- **I_sa**: secondary average current of T_M
- **T**: switching period of Pwr
- **T_on**: turn-on time of T
- **T_off**: turn-off time of T
- **V_o**: output voltage of Pwr
- **V_in**: input voltage of Pwr
- **V_sl**: voltage of slope compensation signal
- **V_err**: output voltage of the error amplifier
- **V_rp**: sensed voltage of Resistor R_p

There are two distinctly different operating modes of power converters, discontinuous and continuous. If a higher power conversion efficiency is concerned, the continuous mode is much more widely used than the discontinuous mode. The purpose of the following analysis is to figure out the criterion of stabilizing the current loop in which a minimum magnitude of the slope compensation has to be added, if the power converter is operating in continuous current mode or if the duty cycle of power converter is greater than 50 percent. Slope $m$ is the down slope; $m = dI_s/dt = V_o/L_s$. Fig. 2 shows the continuous mode current waveform, $I_p$ and $I_s$. $I_{sa} = I_{sp} - (dI_s/2) = I_{sp} - (m/2) \cdot dt$; $I_{sa} = I_{sp} -$
\[ (m/2) \cdot T_{\text{OFF}}; \quad I_{\text{SP}} = I_{\text{SA}} + (m/2) \cdot (T - T_{\text{ON}}). \] The peak voltage \( V_{\text{RP}} \) across the primary current-sensing resistor \( R_p \) is \( V_{\text{RP}} = I_{\text{PP}} \cdot R_p = I_{\text{SP}} \cdot (N_s/N_p) \cdot R_p = [I_{\text{SA}} + (m/2) \cdot (T - T_{\text{ON}})] \cdot (N_s/N_p) \cdot R_p. \) Adding the slope compensation to \( V_{\text{RP}}, \) this feedback signal is stated as \( V_c = V_{\text{RP}} + (V_{\text{SL}}/T) \cdot \Delta T = V_{\text{RP}} + (V_{\text{SL}}/T) \cdot (\Delta T_{\text{ON}} + \Delta T_{\text{OFF}}); \]

\[
V_c = \frac{N_s}{N_p} R_p I_{\text{SA}} + \frac{N_s}{N_p} R_p m T + \Delta T_{\text{ON}} \left( \frac{V_{\text{SL}}}{T} - \frac{N_s}{N_p} R_p \frac{m}{2} \right) + \Delta T_{\text{OFF}} \frac{V_{\text{SL}}}{T}
\]

(1)

Since an amount of energy delivered in a time \( T \) represents power, at the end of one period, power drawn from \( V_{\text{IN}} \) is \( P = L_p I_p^2/(2T) = [L_p \cdot (I_{\text{PP}}^2 - I_{\text{PA}}^2)]/(2T), \) but \( I_{\text{PP}} = I_{\text{PA}} + \Delta I_p = I_{\text{PA}} + (V_{\text{IN}}/L_p) \cdot \Delta T, \)

then

\[
P = \frac{1}{2TL_p} (V_{\text{IN}}^2 T_{\text{ON}}^2) + V_{\text{IN}} \cdot I_{\text{PA}} \frac{T_{\text{ON}}}{T}
\]

(2)

The current \( I_{\text{PA}} \) is an energy which cannot completely deliver to the load during the OFF \( (T_{\text{OFF}}) \) time and still remain in the transformer. Thus the magnitude of the current \( I_{\text{PA}} \) is related to the \( T_{\text{OFF}} \) and \( T_{\text{ON}}. \) It is easily verified from equation (2), that the feedback loop regulates the output of power converter by controlling \( T_{\text{ON}}. \) The output voltage \( V_o \) is sensed and compared to a reference voltage in the error amplifier (EA). The amplified error voltage \( V_{\text{ERR}} \) (voltage loop signal) is fed to a voltage comparator and compared with the \( V_c \) (current loop signal). As shown in Fig. 1, the ON time starts at the clock pulse of oscillator (OSC) and ends when the \( V_c \) ramp equals a level of the \( V_{\text{ERR}}. \) Thereby, the adjustment of \( T_{\text{ON}} \) is in proportion to the magnitude of voltage \( V_c \) and \( V_{\text{ERR}}. \) Mathematically, the relationship between \( V_c \) and \( T_{\text{ON}} \) is \( \partial V_c/\partial T_{\text{ON}} \) is \( \partial V_c/\partial T_{\text{ON}} \approx 0. \) The deviation from equation (1) can be stated as:
\[
\frac{\partial V_c}{\partial T_{ON}} = \frac{V_{SL}}{T} \frac{NS}{NP} R_P \frac{m}{Z}
\]

This can be seen quantitatively as

\[
\frac{V_{SL}}{T} \frac{NS}{NP} R_P \frac{m}{Z}
\]

(3)

If the change of \( T_{ON} \) is out of proportion to the \( V_c \), \( \partial V_c/\partial T_{ON} < 0 \), then the feedback loop will non-linearly oscillate. Thus, the criterion of equation (3) must be satisfied to insure the stable loop.

(B) Advantage II: Slope compensation improve the linearity of the current loop

Before adding the slope compensation, the signal \( V_c \) is equal to \( V_{RF} \):

\[
\Delta I_p = \frac{V_{IN}}{L_p} \Delta T
\]

(4)

\[
V_{RF} = \left( I_{PA} + \frac{V_{IN \Delta T_{ON}}}{L_p} \right) R_P
\]

(5)

This is seen from equation (2), (4), and (5), when the output power remain constant, the \( T_{ON} \) increase and \( \Delta I_p \) decrease as \( V_{IN} \) goes down. The current waveform corresponding to the \( V_{IN} \) and \( T_{ON} \) is shown in Fig. 3. The current feedback loop signal compared with the voltage feedback loop signal will control the output power and regulate the output voltage. It is obvious the control loop will lose the linearity and noise immunity as \( V_{IN} \) goes down. This disadvantage can be improved by adding the slope compensation.

The slope compensation element remains a minimum linearity of the control loop.
\[ V_C = V_{RF} + \frac{V_{SL}}{T} (\Delta T_{ON} + \Delta T_{OFF}) = I_\text{PA} \cdot R_\text{P} + \frac{V_{SL}}{T} \Delta T_{OFF} + \Delta T_{ON} \left( \frac{V_{IN}}{L_\text{P}} \cdot R_\text{P} + \frac{V_{SL}}{T} \right) \]  

(6)

(C) Disadvantage I: A dummy load or the minimum load is required to avoid the unstable oscillation while no load or light load conditions.

The current mode power converter per se are known, it will operate in discontinuous mode while the output is in no load or light load conditions and it may operate in continuous mode while the output power is high or the input voltage is low. A minimum magnitude of slope compensation must be added as equation (3), as long as the power converter operates in the continuous mode. While the power converter is operating in discontinuous mode, its slope compensation included current feedback loop signal \( V_C \) is:

\[ V_C = \frac{V_{IN}}{L_\text{P}} \cdot R_\text{P} \cdot \Delta T_{ON} + \frac{V_{SL}}{T} (\Delta T_{ON} + \Delta T_{OFF}) \]  

(7)

This signal waveform is shown in Fig. 4. It illustrates the mechanism of a nonlinear deviation in the power control. If the signal \( V_{err} \) goes down due to the regulation, its voltage moves from point C to point A or point B will cause a nonlinear deviation. Since the voltage level of point A is equal to point B, but the ON time (\( T_{ON} \)) of point A and point B is different. The difference is (\( T_{ONB} - T_{ONA} \)) which causes a deviation \( P_d \) in the power control.

\[ P_d = \frac{V_{IN}^3}{2TL_\text{P}} (T_{ONB}^2 - T_{ONA}^2) \]  

(8)
Because of this, the effect is then an oscillation which commences at every change in signal \( V_{err} \) and which may continue for some time. Two conventional approaches to solve this problem are: (a) To equip with a dummy load in the output. This yields \( [I_p \cdot R_p > (V_{SL}/T)] \) during the no load or light conditions. However this will consume a power of dummy load. (b) To require consuming a minimum power in the load. However, this cannot meet the requirement of the power management. The embodiment of power management is to manage the system only consuming the power during the operation. Thus no power or less power is consumed during the non-operation (sleep mode). With respect to the power converter in a power management application, how to save the power in the no load or light load conditions is a major requirement.

(D) Disadvantage II: Less than ideal line voltage regulation

Consider how the power converter regulates against line voltage changes. As \( V_{IN} \) goes up, the \( V_o \) will eventually go up. Then after delay in getting through the voltage feedback loop, \( V_{err} \) goes down and the output voltage will be brought back down. Besides the mechanics of this, there is a shortcut correction in the current mode operation. As \( V_{IN} \) goes up, the slope of current \( I_p \) increases and hence, the slope of the ramp of \( V_{rp} \) increases. Now the faster ramp equals \( V_{err} \) and the ON time \( (T_{ON}) \) is shortened. Output voltage changes resulting from input voltage changes will be smaller in amplitude and shorter in duration because of this feed-forward characteristic. The output voltage \( V_o \) is:

\[
V_o = V_{IN} \frac{NS}{ND} \frac{T_{ON}}{T_{OFF}}
\]
By using equation (7), if \( V_c = V_{err} \), then we obtain

$$ T_{ON} = \frac{V_{err}}{\left( \frac{V_{IN}}{L_P} + \frac{V_{SL}}{T} \right)} \tag{9} $$

We can find that the loop gain of this feed-forward characteristic will be reduced by increasing the magnitude of slope compensation \( V_{SL}/T \). Thus, increasing the magnitude of slope compensation will decrease the loop gain of current feedback loop and then reduce the capability of line voltage regulation.

Figures (5) and (6) show two conventional methods of implementing slope compensation. They are unable to solve the problems in the previous description and unable to operate in wide input ranges \( (V_{IN}) \).

**Objects of the Invention**

In view of the above advantages and disadvantages with the prior approach, the object of the present invention is to provide a novel solution to avoid these disadvantages and achieve a wide input range power conversion. Besides, the objects of the present invention are: (a) to improve the power conversion efficiency and save energy; and (b) to shrink the volume of the power converter and save the material costs.

These objects are realized in a novel slope compensation construction which allow the power converter to operate in continuous mode under the medium load or heavy load condition. No minimum load or dummy load is required under the light load or no load conditions. The adaptive function of the present invention enhances the linearity of the control loop in response to a lower input voltage and permits a higher duty cycle \( (T_{ON}/T_{OFF}) \). Therefore, a smaller input capacitor is only needed. In an off-line power converter, this high voltage, high capacity electrolytic capacitor is expensive and large. It is much more
compact and cost effective to use a smaller input capacitor.

Summary of the Invention
In accordance with the present invention, a programmable current source comprises a capacitor, generating a slope signal. This slope signal is added to the current feedback loop for slope compensation. The slope signal is synchronized with the switching signal of the power converter via the connection of a diode; the input of the programmable current source having a resistor, coupled to the voltage feedback loop of power converter, and generating a slope signal in response to the input voltage and output load of the power converter wherein the slew rate and magnitude of the slope signal is responsive to the input voltage and output load, and the signal width of the slope signal is equal to the pulse width of switching signal of the power converter.

Brief Description of the Drawings
Fig. 1 is a simplified circuit illustrating the current mode power converter;
Fig. 2 shows the continuous mode current waveforms;
Fig. 3 shows the current waveform under relatively high and relatively low $V_{in}$;
Fig. 4 shows the current loop feedback signal in which the slope compensation signal is added and illustrates the mechanism of a nonlinear deviation in the power control;
Figs. 5 and 6 show, respectively, two forms of prior art circuits;
Fig. 7 is a schematic diagram illustrating a preferred embodiment of the invention; and
Fig. 8 is the voltage waveform of ripple in the input capacitor.

Detailed Description of Preferred Embodiment
Fig. 1 shows an embodiment of current mode power converter constructed in accordance with the invention.
PWM control \( U_1 \) is a general control circuit for current mode power conversion. The switching signal \( V_{sw} \) (the output of \( U_1 \)) drives a switching MOSFET \( Q_2 \). A transformer \( T_m \) is placed in series with \( V_{in} \) and \( Q_2 \) for the power transfer. Switching frequency is determined by capacitor \( C_s \) and the oscillator (OSC) in \( U_1 \). Because the Latch of \( U_1 \) is set by OSC and reset by the comparator (Comp) in \( U_1 \), the ON time starts at the clock pulse of OSC and ends when the voltage level of the signal from current feedback loop 200 equals the voltage level of signal from voltage feedback loop 150. The voltage feedback loop consists of error amplifier \( U_3 \) and optocoupler \( U_2 \). The output voltage of power converter \( V_o \) is sensed and compared to a reference voltage in the error amplifier \( U_2 \). The optocoupler \( U_2 \) is required for the isolation in an off-line power converter. Otherwise, the amplified error voltage can be directly fed to the comparator of \( U_1 \). Another input to the comparator is the current feedback signal in which the primary current of transformer \( T_m \) is sensed by resistor \( R_p \), and it is coupled to \( U_1 \) via the low pass filter \( R_s \) and \( C_s \). Adaptive slope compensator 100 has a pnp transistor \( Q_1 \) and incorporates resistors \( R_1 \), \( R_2 \), and \( R_3 \) to form a programmable current source. Power is supplied from \( V_{r} \) of \( U_1 \) as a constant voltage (reference voltage) output of \( U_1 \). The output of the programmable current source, the collector of \( Q_1 \), has a capacitor \( C_t \) connected to ground, which serves to produce slope waveform and provides the time constant for the slew rate of the slope signal. A diode \( D_r \) is connected between the output of the programmable current source and the output of \( U_1 \) (\( V_{sw} \)), which serves to synchronize the slope signal 250 with the switching signal \( V_{sw} \) 300. Bridged by the series of \( D_4 \) and \( R_4 \), slope signal 250 is added to the current loop 200. Via resistor \( R_1 \), the input of the programmable current source is connected to any suitable means, exemplified here as \( V_{fb} \), a voltage feedback loop signal,
and thereby the output current of the programmable current source is effected by input voltage $V_{IN}$ and output power $P_o$ of the power converter.

Operation

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The operation of Fig. 7 in accordance with the invention is as follows:

During the ON time ($T_{ON}$), the switching signal $V_{sw}$ is high and diode $D_T$ is OFF, capacitor $C_T$ is charged by the programmable current source. Mathematically this can be stated as:

$$V_{SL} = \frac{I_{R3} \cdot \Delta T}{C_T}$$

If the gain ($h_{FE}$) of Q1 is high enough, then

$I_{R3} = (V_{R2} - V_{EB(Q1)}) / R_3$

$V_{R2} = (V_R - V_{FB}) \cdot \left[ R_3 / (R_3 + R_2) \right].$

The equation can be written as:

$$V_{SL} = \frac{-\Delta T}{R_3 \cdot C_T} \left[ (V_R - V_{FB}) \cdot \frac{R_2}{R_1 + R_2} - V_{EB(Q1)} \right]$$

15 (10)

$$\frac{\partial V_{SL}}{\partial V_{FB}} = -\frac{R_2}{R_3 (R_1 + R_2) C_T} \Delta T$$

(11)

Since the change of $V_{FB}$ is directly proportional to the change of $V_{IN}$ and inversely proportional to the change of output power $P_o$, $\Delta V_{FB} = +K_1 \Delta V_{IN} - K_2 \Delta P_o$, where $K_1, K_2$ are loop gain constants of the voltage feedback loop. Thus, equation (11) can be stated as:

$$\Delta V_{SL} = \frac{R_2}{R_3 (R_1 + R_2) C_T} \Delta T \cdot (-K_1 \Delta V_{IN} + K_2 \Delta P_o)$$

(12)

During the Off time ($T_{OFF}$), the switching signal $V_{sw}$ is low, diode $D_T$ is ON, capacitor $C_T$ is discharged and
the slope signal is reset to zero. Since the slope signal is synchronized with the switching signal, the rising time $\Delta T$ of slope signal is equal to the ON time $T_{ON}$. Thus, equations (10) and (12) can be written as:

$$V_{SL} = \frac{T_{ON}}{R3C_T} \left[ (V_R - V_{FB}) \cdot \frac{R2}{R1 + R2} - V_{SB}(Q1) \right]$$ (13)

$$\Delta V_{SL} = \left( \frac{R2}{R1 + R2} \right) \frac{T_{ON}}{R3C_T} \cdot (-K_1 \Delta V_{IN} + K_2 \Delta P0)$$ (14)

In one specific implementation of the Fig. 7 arrangement, a 50W (Po: 20Vdc/2.5A) off-line power converter, the input voltage is rated 90V$_{AC}$ - 265V$_{AC}$ RMS, using a small input capacitor $C_{IN}$ as 68 uF (microfarad), 400 volt electrolytic device. An EFD-30 ferrite core was used, operating in continuous mode under the medium load and full load. The efficiency of 85% ~ 88% was obtained responding to the change of $V_{IN}$ (90V$_{AC}$ - 265V$_{AC}$). Less than 2 W was consumed under the no load condition. According to the principle of equations (13) and (14) and the measurement in the implementation, the following results are observed:

(a) The operation of power converter is stable under the continuous mode and high duty cycle operation, (e.g. $T_{ON}/T_{OFF} = 8/2$). The slope compensation is increased in response to the increase of output power or the decrease of input voltage $V_{IN}$ respectively, and vice versa. The slope compensation is increased while $V_{IN}$ is decreased, thereby providing enough linearity for a low $V_{IN}$. The ripple voltage waveform of $C_{IN}$ is shown in Fig. 8.

$$\epsilon = \frac{Po \cdot t}{2} \frac{1}{C_{IN}} (V_b^2 - V_a^2)$$

$$C_{IN} = \frac{2 \cdot Po \cdot t}{V_b^2 - V_a^2}; \text{ where } V_b = 1.414 \cdot V_{IN(AC)}$$
Since a low \( V_a \) is permitted, this means a small capacitor \( C_{IN} \) is allowed. The slope compensation is reduced in response to the increase of \( V_{IN} \), thus maintaining the performance of line regulation and audio susceptibilities.

(b) The slope signal will be reduced to zero under the light load and no load conditions. Additionally, the slope signal is synchronized with the switching signal \( V_{SW} \), in which the slope signal is reset to zero at the end of ON time \( (T_{ON}) \). Therefore, the oscillation under the light load or no load is avoided. Thus, the dummy load or minimum load is not required.
What is claimed is:
1. An adaptive slope compensator for compensating the
   current mode power converter comprising:
   a programmable current source which generates
   programmable current;
   a grounded capacitor associated with said
   programmable current to generate the slope signal;
   and
   a switching diode to synchronize said slope
   signal with the switching signal of the power
   converter,
   wherein said slope signal is reset to zero in
   response to the OFF signal of said switching signal;
   an input stage of said programmable current
   source has an input resistor coupled to the voltage
   feedback loop of the power converter to effect the
   magnitude of said programmable current and said slope
   signal;
   wherein the slew rate of said slope signal is
   responsive to the signal of said voltage feedback loop
   during the ON time of said switching signal;
   said slew rate and magnitude of said slope
   signal are directly proportional to the change of input
   voltage of the power converter and are inversely
   proportional to the change of output power of the power
   converter; and
   an output stage of said programmable current
   source has an output diode and an output resistor in
series coupled to the current feedback loop of the power
converter to achieve the slope compensation.
2. An adaptive slope compensator in accordance with
claim 1, wherein
said programmable current source includes said
grounded capacitor at its output terminal to
generate the waveform of said slope signal and
provide a time constant for the adjustment of said
slew rate.
3. An adaptive slope compensator in accordance with
claim 1, wherein
the output stage of said programmable current
source has said switching diode connected to said
switching signal therein for synchronizing said
slope signal.
4. An adaptive slope compensator in accordance with
claim 1, wherein said programmable current source
comprises:
a pnp transistor for the current control;
an emitter resistor connected between the
emitter of said transistor and a constant voltage
source for the current setting;
a base resistor connected between the base of
said transistor and said constant voltage source
for providing the bias to said transistor;
an input resistor operatively connected to the
base of said transistor and said voltage feedback
loop for programming the magnitude of said
programmable current;
wherein said programmable current is linearly
responsive to said signal of said voltage feedback loop;
a filter capacitor positioned in the base of
said transistor to eliminate the switching noise of the
power converter.
5. An adaptive slope compensator in accordance with
claim 1, wherein
the magnitude of said signal of said voltage feedback loop is directly proportional to the change of input voltage and is inversely proportional to the change of output power.
Fig. 1
Fig. 3

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SUBSTITUTE SHEET (RULE 26)
Fig. 5
INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/16544

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) : H02M 5395
US CL : 363/97
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tbody>
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<td>US 5,717,322 A (Hawkes et al) 10 February 1988 (10.02.88), see entire document</td>
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B. FIELDS SEARCHED
Minimum documentation searched
Classification System: U.S.

363/21, 95, 97, 131
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