Adaptive Off–Time Control For Variable-Frequency, Soft-Switched Flyback Converter At Light Loads

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Abstract - **The soft switching of a flyback converter can be achieved by operating the circuit in the critical conduction mode. However, the critical-mode operation at light loads cannot be maintained due to a very high switching frequency and the loss of the output voltage regulation. A control which regulates the output down to the zero load and maintains soft switching at light loads is proposed. The proposed control scheme was implemented in the 380 V/19 V, 65 W flyback dc/dc converter.**

I. INTRODUCTION

Due to the minimum number of semiconductor and magnetic components, a flyback converter is a very attractive candidate for off-line low-cost power supplies which require input/output isolation. Since the voltage on the primary switch at the turn-on instant is high and the associated capacitive turn-on loss is substantial, the switch soft turn-on is highly desirable. The soft switching is also helpful in reducing the size and loss of the EMI filter. The soft turn-on of the primary switch is accomplished in the flyback converter operating in the critical conduction mode, i.e. at the boundary of Continuous and Discontinuous Conduction Modes (CCM/DCM). The critical mode of operation requires a Variable Frequency (VF) control to regulate the output voltage against input-voltage and load variations. Operation of the VF flyback converter in the critical mode is discussed in [1]-[4]. However, the VF critical-mode control suffers from a wide frequency range and loss of the output voltage regulation at light load. Namely, for this control, the switch on-time should decrease, as the load current decreases. However, since the minimum on-time of the controller is limited by its internal delays, the converter operating in the critical mode cannot maintain the output regulation at light load.

This problem can be alleviated by limiting the minimum controller off-time to a fixed value, so that converter switches from the critical operation mode at high load to the DCM with constant off-time at light load, as implemented in [4], [5]. However, it was found experimentally that the constant off-time control could not maintain the output regulation as the load current approaches zero value. The control implementations in [4], [5] also do not provide soft switching at light load.

The objective of the paper is to propose a simple VF converter control which maintains the output regulation and soft switching in the entire load range.
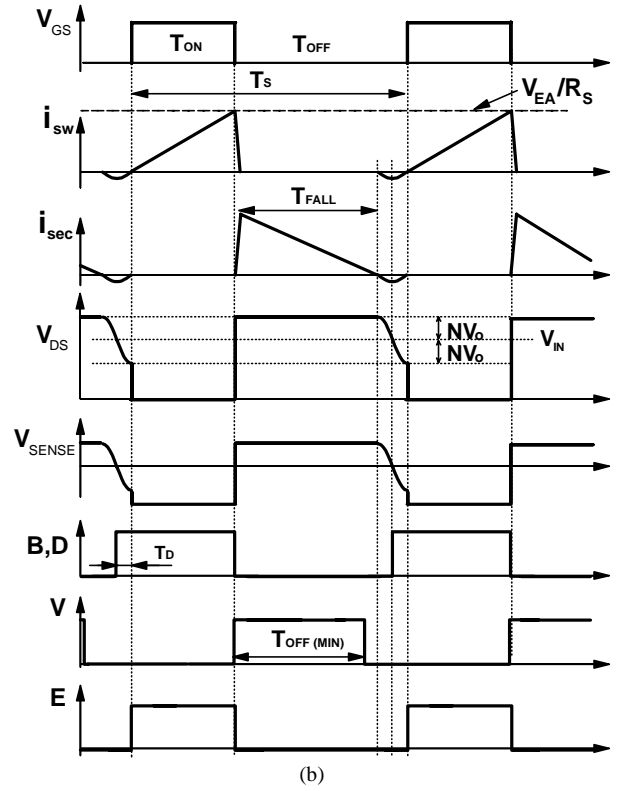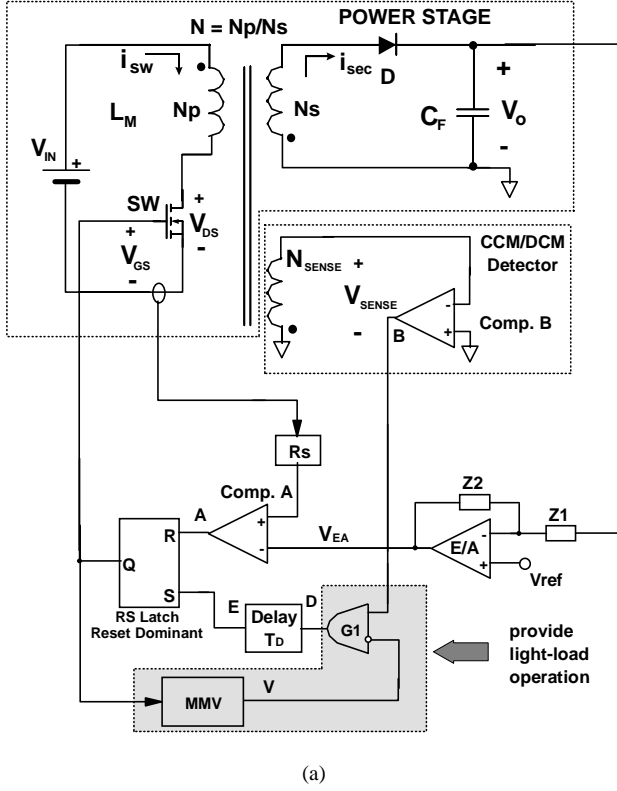
II. CONVENTIONAL OFF-TIME CONTROL OF VF FLYBACK CONVERTER AT LIGHT LOAD

A. Principle Of Operation

The functional diagram of the VF flyback converter with constant off-time control at light load and its waveforms are shown in Fig. 1. The zero crossing of the secondary current is sensed by the CCM/DCM detector, which monitors voltage V_{SENSE} across sensing winding N_{SENSE}. After secondary current i_{SEC} reaches zero, the magnetizing inductance of the transformer starts resonating with the parasitic capacitances of the primary switch and secondary rectifier. As a result, voltage V_{SENSE} also resonates, as shown in Fig. 1b. When voltage V_{SENSE} goes negative, detector output signal B becomes high. The error amplifier EA provides the reference signal V_{EA}, which is compared with the sensed switch current $i_{SW} \cdot R_S$. When the switch current reaches the V_{EA}/R_S value, the RS latch, which controls the gate drive, is reset. The way the latch is set depends on the load. At heavy load (Fig. 1b), secondary current fall time T_{FALL} is longer than the duration of the output pulse V of the Monostable Multivibrator (MMV). When the secondary current goes below zero, detector output signal B changes from "0" to "1", propagates through gate G1, and after delay T_D sets the latch. Delay T_D between the secondary current zero-crossing and primary switch turn-on provides the switch turn-on with the voltage $V_{IN} - N \cdot V_O$ across it. As a result, the switching loss is substantially reduced. At light load (Fig. 1c), the secondary current fall time is shorter than the MMV output pulse duration. The output signal of CCM/DCM detector cannot propagate through gate G1 until the MMV output pulse expires. Therefore, at light load, the switch off-time is determined by the MMV output pulse duration.

B. Limitations

The analysis in this Section facilitates the explanation of limitations of the constant off-time control at light load. All converter components were assumed ideal for analysis purposes. The analysis was performed for the 380 V/19 V, 65 W flyback converter. The full-load switching frequency of the converter was selected to be 35 kHz which is above the audible range. The corresponding transformer primary-side magnetizing inductance was $L_M = 1.27$ mH. To keep the switch voltage stress below 600 V, the transformer has turns ratio N = 5:1.

(a)

(b)

(c)

Fig. 1. Conventional control of VF flyback converter: (a) functional diagram; (b) heavy-load waveforms; (c) light-load waveforms.

The peak value I_{PEAK} of switch current I_{SW} is related to the on-time T_{ON} and fall time of the secondary current T_{FALL} as:

$$I_{PEAK} = \frac{V_{IN} \cdot T_{ON}}{L_M}, \qquad (1)$$

$$I_{PEAK} = \frac{V_O \cdot T_{FALL}}{L_M} \cdot N, \qquad (2)$$

Load current is equal to the average value of the secondary current: $I_O = \frac{I_{PEAK} \cdot T_{FALL}}{2 \cdot T_S} \cdot N. \qquad (3)$

From (1) and (2), the relationship between the on-time and fall time is: $T_{ON}/T_{FALL} = M \cdot N, \qquad (4)$

where $M = V_O/V_{IN}$ is the voltage conversion ratio.

From (2) and (3), one can derive:

$$I_O = \frac{V_O \cdot (N \cdot T_{FALL})^2}{2 \cdot L_M \cdot T_S}. \qquad (5)$$

In the critical mode,

$$T_S = T_{ON} + T_{FALL}. \qquad (6)$$

Combination of (4), (5) and (6) produces expressions:

$$T_{FALL} = \frac{I_O}{V_O} \cdot \frac{2 \cdot L_M}{N^2} \cdot (1 + M \cdot N), \qquad (7)$$

$$T_S = \frac{I_O}{V_O} \cdot \frac{2 \cdot L_M}{N^2} \cdot (1 + M \cdot N)^2. \qquad (8)$$

It follows from the last expression that in the critical mode the switching frequency is inversely proportional to the load current. Theoretically, the switching frequency approaches infinity when the l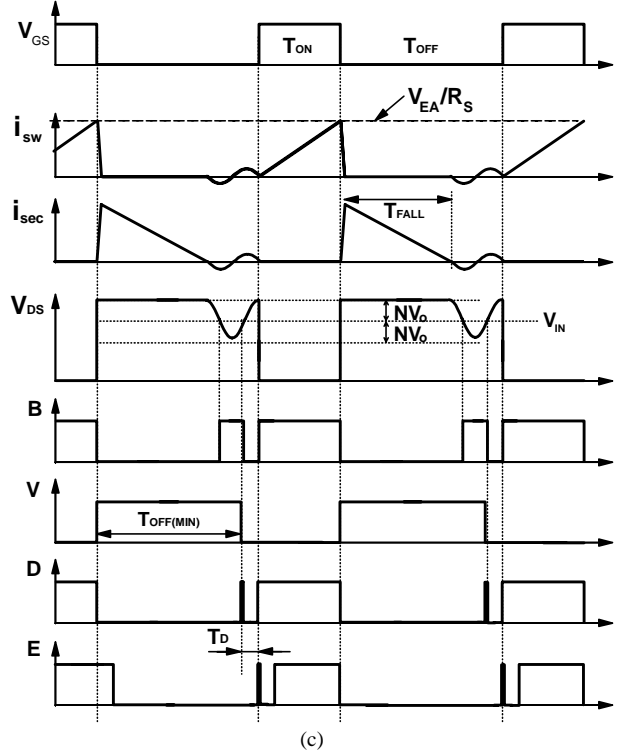oad current approaches zero. This implies that in the critical mode the converter would suffer from an extremely wide frequency range and excessive switching losses at light load.

Another limitation of the critical mode operation at light load comes from the fact that, practically, the minimum on-time of the controller is limited to 0.5-0.9 us by the delays of the comparator and logic circuitry of the controller IC. If the required on-time becomes smaller than the control IC minimum on-time, the controller can no longer maintain the output regulation. Reduction of the controller minimum on-time time is possible by refining the IC circuitry, but it causes a sensitive increase of the IC cost.

From (4) and (7), the minimum output power value P_{Ocrit}^{min} at which the controller is able to regulate the output in the critical mode is equal:

$$P_{O\,crit}^{min} = \frac{T_{ON}^{min} \cdot V_{IN} \cdot V_O \cdot N}{L_M \cdot (1 + M \cdot N)} \qquad (9).$$

For T_{ON}^{min} =0.8 μs, $P_{O\,crit}^{min}$ value computed from (9) is 8.6 W. The switching frequency which corresponds to $P_{O\,crit}^{min}$ is close to 250 kHz. For lower loads, the output-voltage regulation of the VF converter in the critical mode cannot be maintained.

The output regulation at the loads below P_{Ocrit}^{min} can be achieved by operating the converter in DCM with the constant off-time T_{OFF}^{min}. For the constant off-time control, $T_S = T_{ON} + T_{OFF}^{min}$, and expressions (4), (5) are employed to derive the minimum output power at which the controller is still able to regulate the output with constant off-time:

$$P_{Odcm}^{min} = \frac{V_{IN}^{2} \cdot T_{ON}^{min^2}}{2 \cdot L_M \cdot (T_{ON}^{min} + T_{OFF}^{min})} . \qquad (10)$$
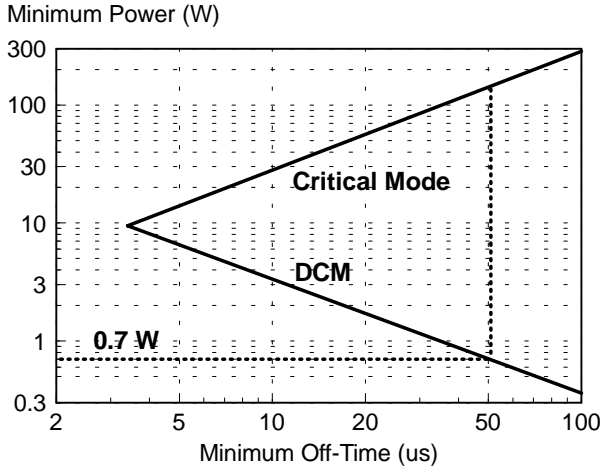

Fig. 2. Calculated minimum load attainable in critical conduction mode and in DCM for conventional off-time control.

To facilitate explanation of the constant off-time control limitation, the minimum output power attainable in the critical mode and in DCM is graphed in Fig. 2 as a function of the minimum off-time. The minimum output power attainable with the constant off-time control was computed based on (10), and the minimum output power attainable with the critical-mode control was computed based on (4) and (9). If the converter is

expected to operate down to 0.7 W load, then, based on Fig. 2, the minimum off-time should be chosen to be 51 μs. However, for T_{OFF}^{min} =51 μs, the critical-mode operation starts only at the load above 100 W. This means that the 65-W converter will operate in DCM in the entire load range. As the T_{OFF}^{min} value increases, the output regulation range increases, but at the same time the load level at which converter shifts from the critical mode to DCM increases. **The trade-off between the output regulation at light load and critical mode of operation at high load cannot be satisfied for the conventional off-time control.**

Also, as can be seen from Fig. 1c, the conventional control loses soft switching at light loads.

III. PROPOSED OFF-TIME CONTROL OF VF FLYBACK CONVERTER AT LIGHT LOAD

A. Principle Of Operation

The functional diagram of the proposed control is shown in Fig. 3a. Heavy-load waveforms of the proposed control coincide with those of the conventional control. Its key waveforms at light load are shown in Fig. 3b.

To solve the problem of the output regulation at light load, the proposed control adaptively increases the off-time as the load decreases. To implement the adaptive control, the MMV pulse duration is adjusted in accordance with the error-amplifier output signal V_{EA} which indirectly carries information about the load.

The MMV implementation is shown in Fig. 4. The duration of the MMV output pulse V is adjusted by varying the comparator threshold as a function of the error-amplifier output signal V_{EA}. In Fig. 4a, capacitor C is charged through the parallel combination of resistors R1 and R2 during the on-time, and is discharged through resistor R1 during the off-time. Time constant $\tau_1 = R1 \cdot C$ is selected to be comparable with the maximum T_{OFF} value, while time constant $\tau_2 = (R1 \| R2) \cdot C$ should guarantee the charge of the capacitor to the Zener diode breakdown voltage V_{ZD} during T_{ON}^{min}. Zener diode ZD assures charging of capacitor C to the same level independently of the magnitude of the gate-drive signal.

The relationship between the off-time and the signal V_{EA} on the inverting input of the MMV comparator is:

$$V_{EA} = V_{ZD} \cdot exp(T_{OFF}^{min} / \tau_1). \qquad (11)$$

At the switch turn-off instant,

$$V_{EA} = I_{PEAK} \cdot R_S . \qquad (12)$$

Solution of the equations (1), (9), (11), and (12) produces the dependence of the off-time upon the output power in DCM which is plotted in Fig. 5. Fig. 5 also contains a plot of the on-time versus the load. The computed curves consist of two different pieces. For the load above 1.5 W, the on-time stays above its minimum value T_{ON}^{min}, and both T_{ON} and T_{OFF} change in response to the load variation.

(a)

(b)

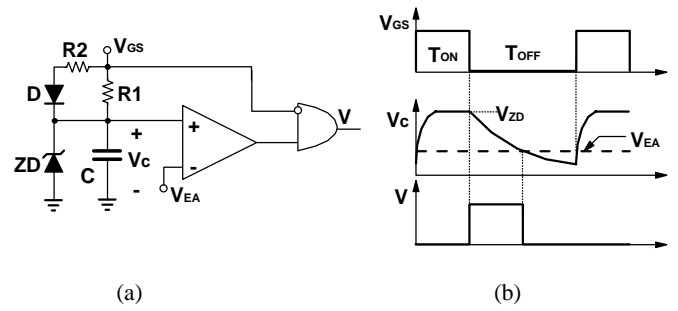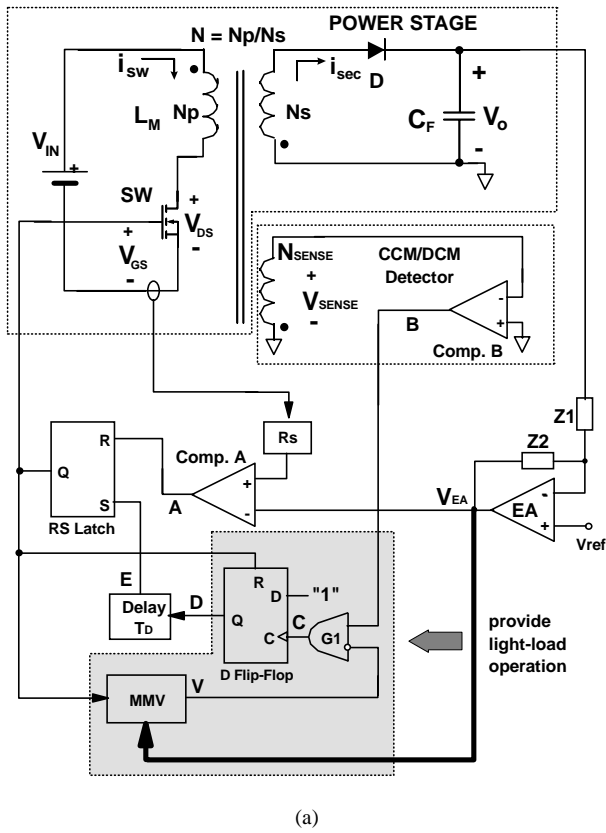Fig. 3. Proposed VF Flyback Converter Control: (a) functional diagram; (b) light-load waveforms.

Fig. 4. Implementation of Monostable Multivibrator with a variable pulse width: (a) functional diagram; (b) key waveforms.
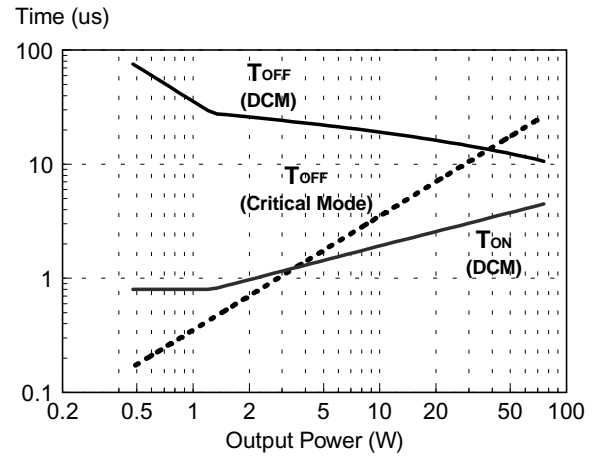

Fig. 5. Calculated on-time and off-time for the proposed control.

For the load below 1.5 W, the on-time has reached its minimum value, and only the off-time varies with load change. The relationship between the off-time in the critical mode and the load current is also plotted in Fig. 5. The intersection of the T_{OFF} curves corresponding to the critical mode and DCM shows the point where the converter changes its mode of operation. The change of the operation mode occurs at the 38 W load level.

B. Soft Switching At Light Load

To retain soft switching at light load, the proposed control turns on the switch when voltage V_{DS} reaches the resonance valley. As shown in Fig. 3a, the voltage V_{DS} minimum is detected by sensing the instant when voltage V_{SENSE} changes its polarity from positive to negative, and, then, delaying the turn-on instant for a quarter of the resonant period. To turn-on the switch in the resonance valley, the D flip-flop is added to the controller circuitry. After MMV output pulse V has expired, the D flip-flop waits for voltage V_B to cross the zero level in the negative direction. As soon as this event happens, the D flip-flop changes its output state from "0" to "1", and after delay T_D turns on the switch. With delay T_D taken into account, the primary switch turn-on occurs exactly in the resonance valley of its drain-source voltage waveform.

C. Design Considerations

The control circuitry determines the output power $P_{O\,crit}^{min}$ at which the converter shifts from the critical mode of operation to DCM. The $P_{O\,crit}^{min}$ level is usually selected based on considerations of the circuit efficiency and frequency range. As the $P_{O\,crit}^{min}$ value decreases, the operating frequency range increases. The desirable $P_{O\,crit}^{min}$ value can be achieved by proper selection of Zener diode breakdown voltage V_{ZD} and time constant $\tau_1 = R1 \cdot C$ of capacitor C in Fig. 4.

The calculated relationship between $P_{O\,crit}^{min}$, maximum operating frequency and design parameter $T = (L_M/V_{IN}) \cdot (V_{ZD}/R_S)$ for different τ_1 values is plotted in Fig. 6. As voltage V_{ZD} increases, the $P_{O\,crit}^{min}$ level increases, and the maximum switching frequency decreases. The value of τ_1 is limited by several factors. A lower τ_1 value can result in a nearly zero voltage across capacitor C at the end of the off-time, causing the MMV comparator to become more susceptible to noise. A higher τ_1 value can result in an undesirably high $P_{O\,crit}^{min}$ level, as can be seen from Fig. 6. These considerations determine the design range for the constant τ_1.
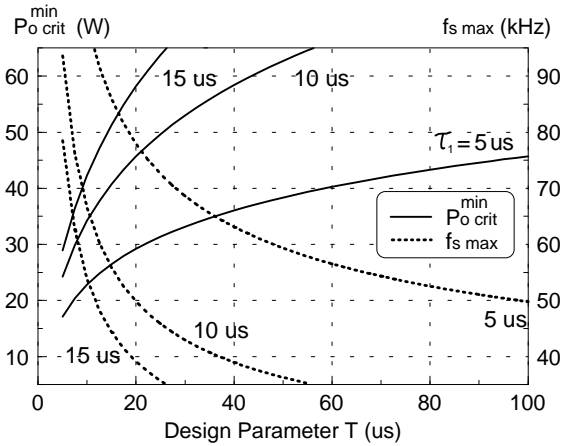

Fig. 6. Calculated dependence of minimum critical-mode load power and maximum switching frequency on control design parameters.

The calculated dependence of the switching frequency upon load is plotted in Fig. 7 for selected design parameters. In the 38-65 W load range, the converter operates in the critical mode, and the switching frequency increases from 35 to 58 kHz as the output power decreases. In the 1.5-38 W range, the converter operates in DCM with variable on and off times. The frequency starts decreasing and drops to 35 kHz at the 1.5 W load. At this power level, the on-time reaches its minimum value (0.8 µs). If the load is reduced below 1.5 W, the converter operates with the constant on-time, and the off-time grows rapidly as the load decreases. At the minimum load (0.7 W), the frequency drops to 19 kHz. Thus, the proposed control provides the converter operation in the entire load range with the frequency variation from 19 to 58 kHz.
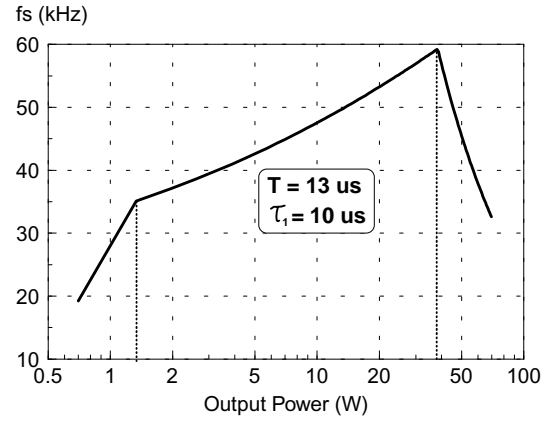

Fig. 7. Calculated switching frequency versus load for proposed control.

IV. HARDWARE EVALUATION OF PROPOSED CONTROL

Experimental waveforms of the 380 V/19 V, 65 W flyback converter with proposed control for heavy, light, and very light loads are shown in Fig. 8.
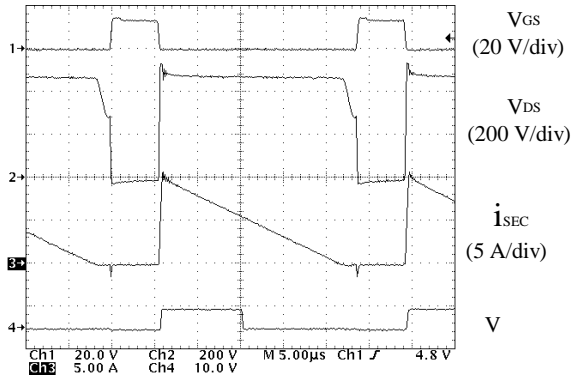
At full load (Fig. 8a), the duration of the MMV output pulse V is shorter than the secondary-current fall time. At the instant when the secondary current falls to zero, the output signal B of the CCM/DCM detector in Fig. 3a propagates through gate G1 and after delay T_D turns on the switch. As a result, the converter operates in the critical mode.

As the load decreases from 65 W to 10 W, the duration of the MMV output pulse increases from 9.5 to 11.6 µs, and it becomes longer than the fall time of the secondary current (Fig. 8b). The CCM/DCM detector output signal cannot turn-on the switch until the MMV output pulse expires. As a result, the converter operates in DCM.
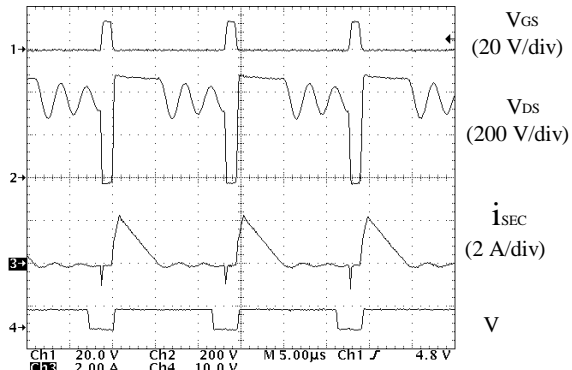
As can be seen from Figs. 8a and 8b, the switch turns on in the resonance valley with the minimum voltage across it both at heavy and light loads.

At very light load (Fig. 8c), the duration of the MMV output pulse increases to 24.3 µs. The resonance decays significantly during the off-time, and the voltage on the switch at the turn-on instant is close to V_{IN}.
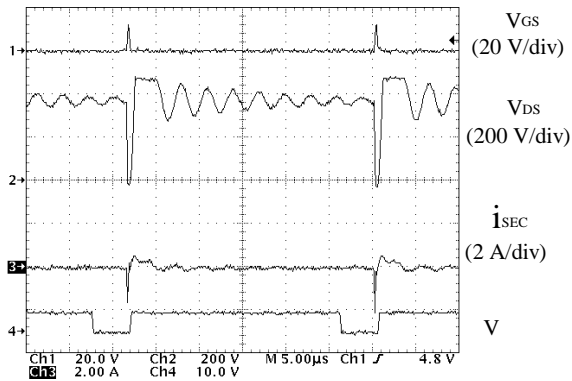
The measured switching frequency is plotted versus load in Fig. 9. For comparison, Fig. 9 also shows the calculated switching frequency curve. The converter operates in the critical mode in the 35-65 W load range. For loads below 35 W, the converter operates in DCM. When the load decreases below 2-3 W, the on-time reaches its minimum value requiring the controller to increase the off-time significantly. For this reason, the switching frequency drops down for a load below 2-3 W. This frequency drop is an additional benefit of the proposed control since it reduces the switching loss at very light load.
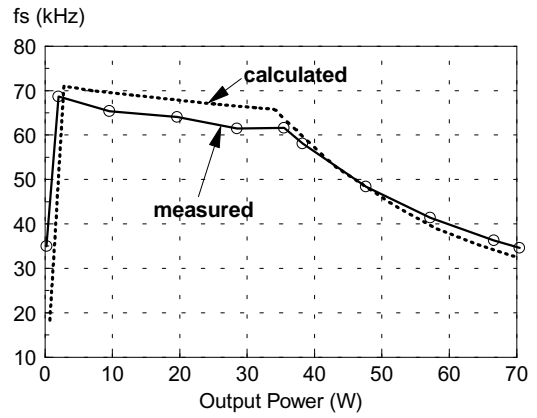
Fig. 9. Measured switching frequency of experimental prototype vs. load.

The shape of the frequency curves in Fig. 9 is related to the internal structure of MC34262 IC which was used in the control circuitry. This IC is intended for PFC applications and has an internal multiplier whose input/output characteristic is responsible for the curves' appearance.

V. SUMMARY

It was demonstrated that the constant off-time control of the VF flyback converter cannot regulate the output as the load current approaches a zero value. A simple adaptive control was proposed which regulates the output down to zero load. The proposed control also maintains the soft-switching at light loads. An additional advantage of the adaptive control is the switching frequency reduction at light loads. The proposed control was successfully implemented in the 380 V/19 V, 65 W flyback converter.

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[3] "TDA 4605-3 Control IC for Switched-Mode Power Supplies Using MOS-Transistor", *Siemens Data Sheet and Application Note*.

[4] Critical Conduction GreenLine SMPS Controller, *Motorola Analog IC Device Data. Rev. 1*, Document MC33364/D.

[5] UC3852 High Power Factor Preregulator, *Unitrode Product and Applications Handbook 1995-96*, pp. 6-278 - 6-282.

Fig. 8. Experimental waveforms of VF flyback converter with Schottky rectifier: (a) Po = 70 W; (b) Po = 10 W; (c) Po = 0.4 W.