

Design Note

DN-SMPS Singlestage

CoolSET™

Design of 30W Off-Line SMPS using CoolSET ICE2B265

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Power Management & Supply



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1. Introduction

The CoolSET ICE2B265 is an integrated pulse width modulator with built in CoolMOS. It is an inexpensive controller combined with the CoolMOS power switch with which designers can obtain all the stringent requirements imposed on the present modern Switched Mode Power Supply (SMPS) like very low standby power, few external components count and minimized PCB size. This application note provides beside functional description of the ICE2B265, it presents also the design of simple low cost and high efficient 30W Flyback SMPS circuit.

2. Block Diagram

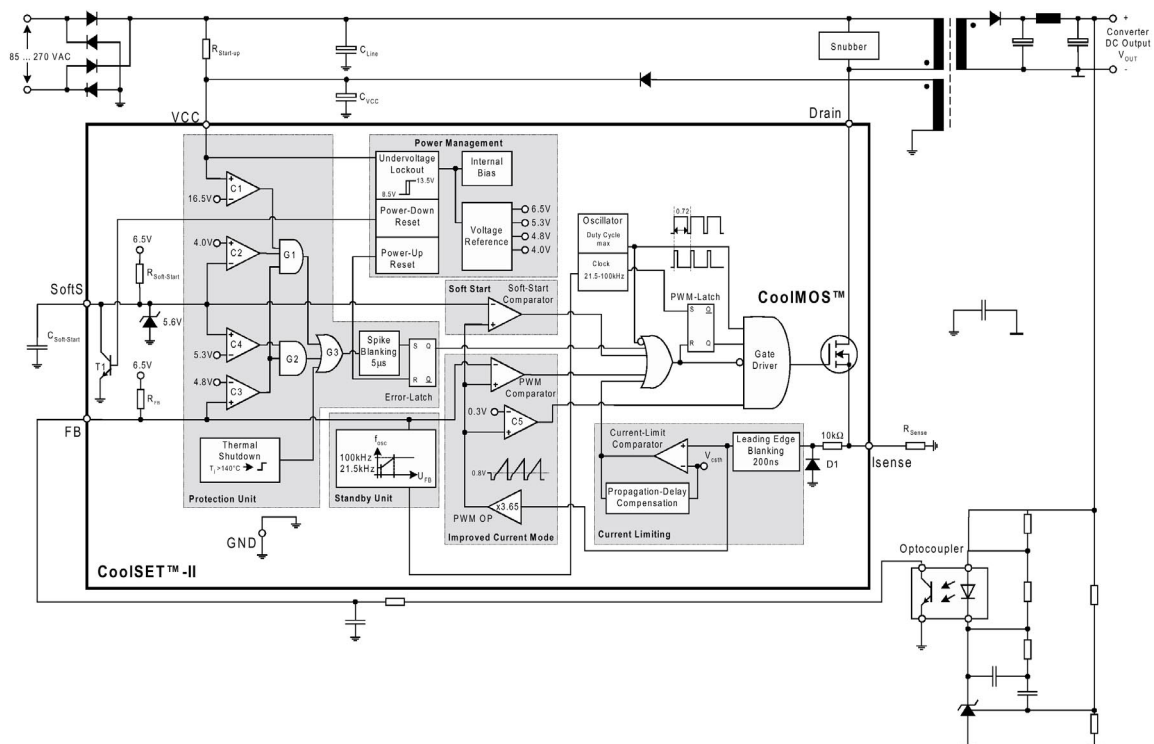


Fig.1. Block diagram of ICE2B265P

The control section of the CoolSET provides several special enhancements to satisfy the needs for low power standby and protection features. It consists of 5 main units, the Power Management, the

Softstart, the Improved Current Mode, the Current Limiting, the Standby and the Protection Unit. The Standby Unit enables the frequency reduction to lower the power consumption in standby mode. The

frequency reduction is limited to 21kHz to avoid audible noise. In case of failure modes like open loop, overvoltage or overload due to short circuit the device switches into Auto Restart Mode, which is control by the Protection Unit. With the patented Propagation Delay Compensation circuit integrated in the Current Limiting Unit, the peak current limitation can be controlled precisely. It leads to more cost efficient dimension of the transformer and the secondary diode.

3. Power Management

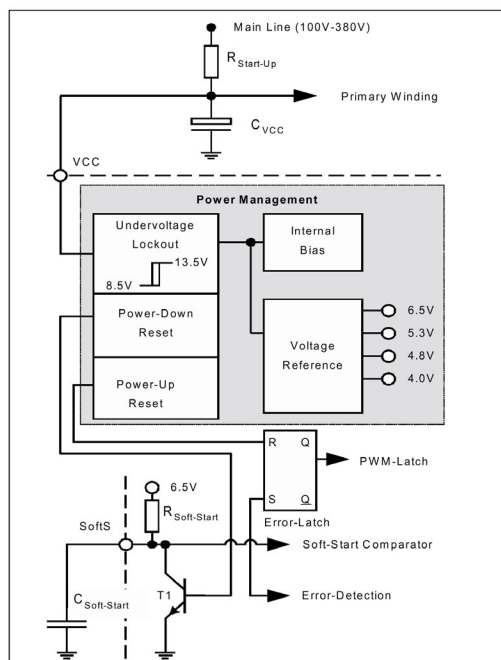


Fig.2. Power Management Unit

Fig.2 shows the Power Management Unit of the IC. The external supply voltage V_{CC} is monitored by the Undervoltage Lockout. The external capacitor C_{VCC} is charged up by the current through the $R_{START-UP}$, when the SMPS is plugged to the main line. The IC remains inactive before V_{CC} reaches the on-threshold $V_{CCON}=13.5V$. The current consumption of the IC at this moment is max. 55uA. When the on-threshold is exceeded, the IC is activated:

- ❑ The internal bandgap generates a reference voltage $V_{REF}=6.5V$ to supply the internal circuit.
- ❑ The internal Error-latch in the protection unit is reset by the Power Up Reset. The Error-latch flip-flop is

then ready to shut down the gate drive if the Protection Unit is activated.

- ❑ The soft-start transistor switch T_1 is released by the Power-Down Reset. The current through $R_{SOFT-START}$ starts to charge the external soft-start capacitor $C_{SOFT-START}$. The soft-start is then activated.

To avoid uncontrolled ringing at switch-on a hysteresis at the Undervoltage Lockout is implemented which means that switch-off is only after active mode when V_{CC} falls below 8.5V.

When V_{CC} falls below the off-threshold $V_{CCOFF}=8.5V$ the internal reference is switched off and the Power Down Reset let the transistor switch T_1 to discharge the soft-start capacitor $C_{SOFT-START}$. Thus it is ensured that the soft-start is always activated at every switch-on.

4. Start-up delay

During startup, C_{VCC} is charged by the current through $R_{START-UP}$. The IC is activated only when the V_{CC} reaches the on-threshold of $V_{CCON}=13.5V$. Because of the very low IC current consumption before activation, high value startup resistor can be used to minimize power loss in start-up resistor. The value of $R_{START-UP}$ and C_{VCC} will effect the startup delay time, which can be estimated by using equation as follow:

$$t_{\text{delay}} = \frac{C_{VCC} \times V_{CCON}}{\frac{V_{1IN}}{R_{START-UP}} - I_{VCC1}} \quad (1)$$

t_{delay} is the duration of the startup time from the moment the SMPS is plugged to the main line until the IC is activated. V_{1IN} is the rectified line input voltage and I_{VCC1} is the current consumption of the IC before activation. Fig.3 shows the $t_{\text{start delay}}$ of the actual SMPS with $R_{START-UP} = 2 \times 470k\Omega$, $C_{VCC}=47\mu F$ and $V_{1IN} = 380V$. (1) indicates that the start-up delay time depends not only on the main input voltage but also mainly on the value of $R_{START-UP}$ and C_{VCC} . The t_{delay} can be shortened by reducing the $R_{START-UP}$ value. However, the loss at $R_{START-UP}$ will increase. It has to be compromised between shorter startup delay time and loss at startup resistor.

Startup circuit with transistor switch can be implemented to achieve startup without losses and constant shorter delay time.

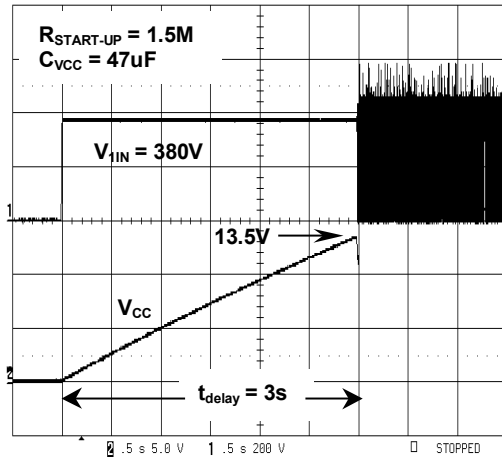


Fig.3. Start-up delay time.

5. Improved Current Mode

In Current Mode the primary current is sensed by the sense resistor R_{CS} (Fig. 4). The sense voltage V_{CS} is amplified 3.65 times for comparison with FB signal by the PWM Comparator. The current flow is terminated by resetting the PWM-Latch, when the sense voltage reaches the level of the FB signal, which is the program level of the output control loop.

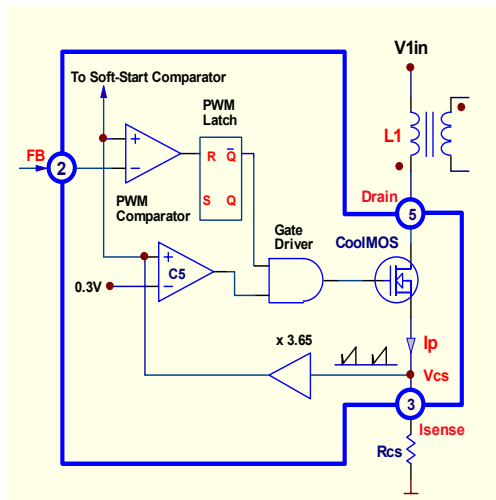


Fig.4. Current Mode Control

Thus, the turn-on time of the power MOSFET as well as the peak primary current is well defined by the level of the FB signal. For flyback converter with discontinuous current operation the power stored in the primary inductor is represented by the equation

$$P = \frac{1}{2} \times L \times f \times i_p^2 \quad (2)$$

Where P is the power stored in the primary inductor, L is the primary inductor, f is the switching frequency and i_p is the peak primary current.

As can be seen, the line-input voltage does not appear in (2). One of the advantages of the Current Mode is that the line variation does not influence the regulation of the output voltage. However, the Current Mode is extremely susceptible to noise on the sense voltage. A noise spike is generated each time the power Mosfet switch is turned on which might turn off the driver immediately especially when the power is small and the FB signal is low.

To improve the Current Mode during light load, a voltage ramp is implemented in the IC.

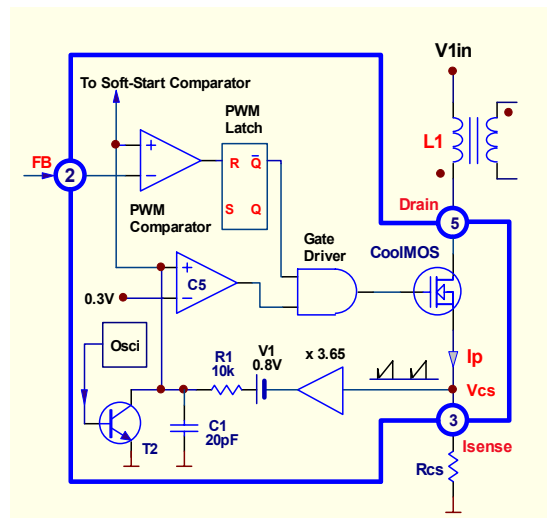


Fig.5. Improved Current Mode

The amplified current sense voltage v_{CS} is superimposed on the voltage ramp, which is built by the switch T_2 , the voltage source V_1 and 1st order low pass filter composed of R_1 and C_1 (see Fig.5).

Fig.6. Normal Load Condition

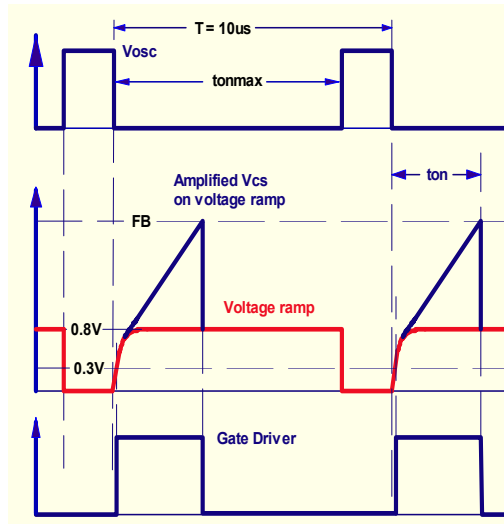


Fig.6 shows the effect of the Voltage Ramp in normal load condition. The switch T_2 is opened at the falling slope of the oscillator. It enables the Voltage Ramp to rise. The Gate Driver turns on the power MOSFET when the Voltage Ramp reaches 0.3V. The primary current starts to flow and is sensed by R_{CS} . The current sense voltage V_{CS} is amplified 3.65 times by the PWM OP, which is then superimposed on the Voltage Ramp. The current flow is terminated when the amplified sense voltage on the Voltage Ramp reaches the FB voltage level.

In case of light load (see Fig.7) or no load, the current sense voltage V_{CS} is so small that only the Voltage Ramp remains as a well defined signal for the comparison with the FB-signal.

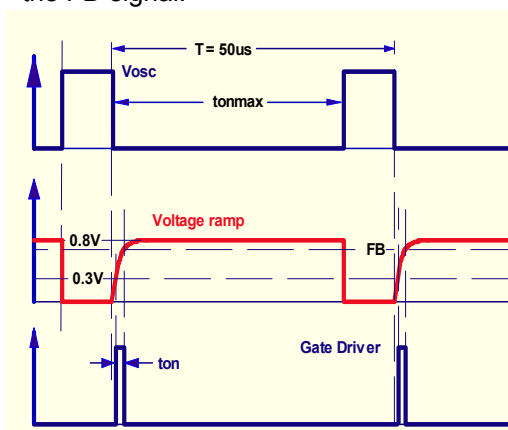


Fig.7. Light Load Conditions

The slope of the Voltage Ramp then controls the turn-on time of the Gate

Driver. The Gate Driver is turned on only when the Voltage Ramp exceeds 0.3V due to the Comparator C_5 . The turn-on time can then be continuously reduced to zero by decreasing V_{FB} below that threshold.

6. Soft-Start

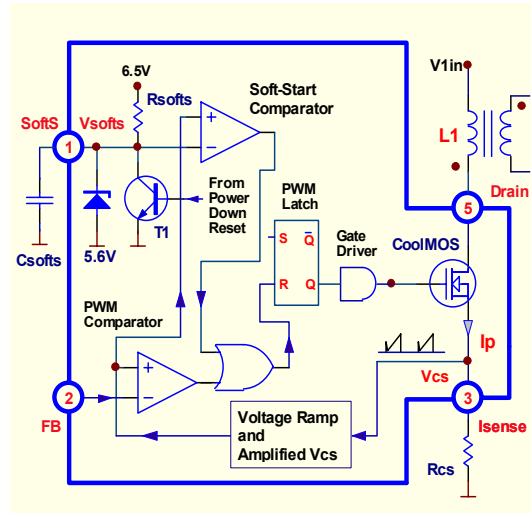


Fig.8. Soft-Start

The Soft-Start voltage V_{SOFTS} is generated by charging the external capacitor C_{SOFTS} through the internal pullup resistor R_{SOFTS} (see Fig.8). The Soft-Start comparator compares the Soft-Start voltage V_{SOFTS} at the negative input with the ramp voltage of the superimposed Voltage Ramp at the positive input. In Soft-Start phase V_{SOFTS} is always smaller than the Feedback Voltage V_{FB} . In this case V_{SOFTS} defines the pulse width of the Gate Driver through the Soft-Start Comparator by resetting the PWM-Latch. The Soft-Start phase is completed when V_{SOFTS} reaches 5.3V (Fig.9). The Soft-Start time is then defined by

$$T_{SOFT-START} = 1.69 \times R_{SOFTS} \times C_{SOFTS} \quad (3)$$

The transistor switch T_1 at Soft-Start is controlled by the Power Down Reset. It is to ensure that the Soft-Start is always activated at the restart of the IC after power down or in Auto Restart mode.

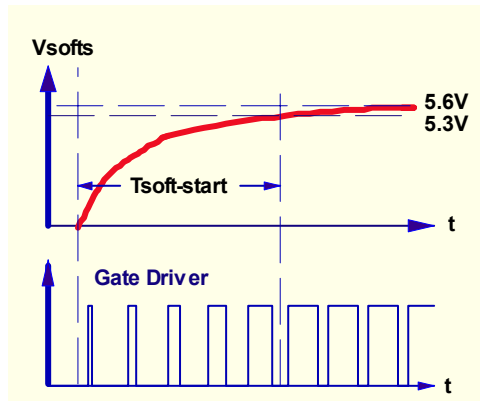


Fig.9. Soft-Start Phase

The Soft-Start voltage V_{SOFTS} is used not only for minimization of current and voltage stresses on the external power MOSFET switch during start-up, it is also used for activation of the Protection Unit (Fig.10).

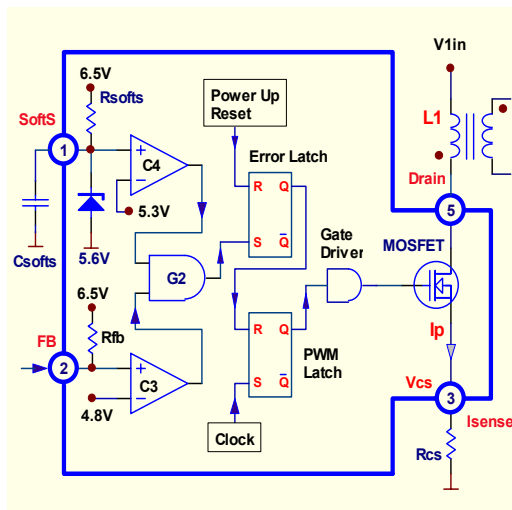


Fig.10. Activation of Protection Unit

When the Soft-Start phase is over ($V_{SOFTS} > 5.3V$), the Error Latch will be activated by Comparator C_4 if the feedback voltage V_{FB} does not drop below 4.8V, which means that the output voltage V_{OUT} at the secondary side of the SMPS does not reaches its nominal level. To ensure proper start-up of the SMPS, the duration of the Soft-Start phase has to be long enough to enable V_{OUT} to rise to its nominal value. This will cause the control

loop to pull down the level of the feedback signal V_{FB} below 4.8V (see Fig.11).

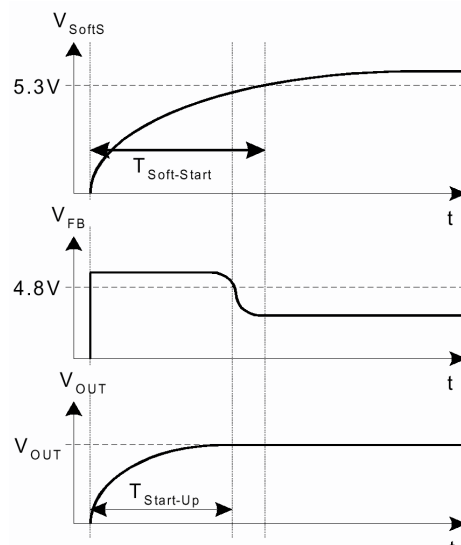


Fig.11. Start-up Phase

7. Oscillator and Frequency Reduction

The oscillator, which generates the switching frequency $F=67kHz$, is integrated in the IC. The oscillator is adjusted so that the Gate driver pulse can reach a maximum duty cycle of $D_{MAX} = 0.72$.

The frequency of the oscillator can be influenced by the feedback voltage V_{FB} as shown in Fig.12. This feature allows a SMPS to operate at lower frequency at light loads thus lowering the switching losses while maintaining good cross regulation performance and low output ripple. The power consumption of the whole SMPS can be reduced very effectively at light load. The minimal reachable frequency is limited to 20kHz to avoid audible noise in any case.

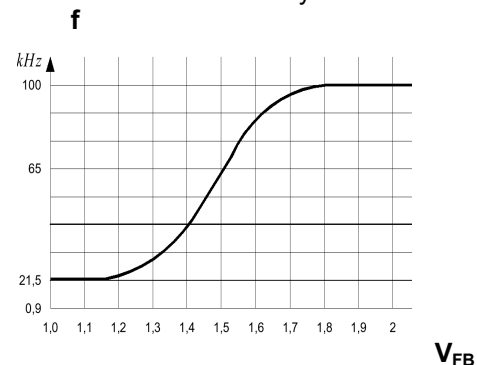


Fig.12. Frequency Reduction vs V_{FB}

8. Current Limiting

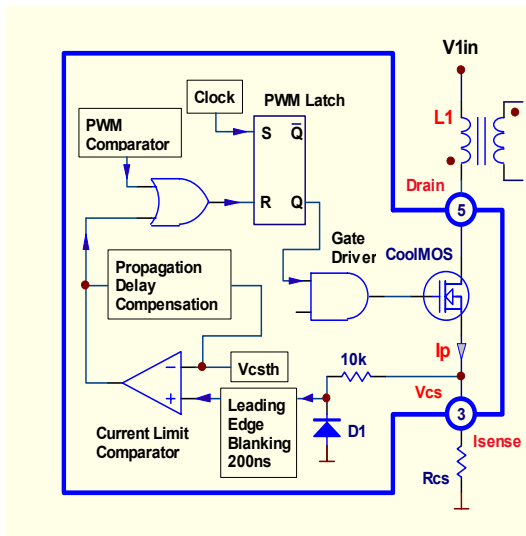


Fig.13. Current Limiting

The cycle by cycle current limiting is performed by the Current Limit Comparator (see Fig.13). The primary current I_P is converted into a sense voltage V_{CS} by an external sense resistor R_{CS} . The sense voltage V_{CS} goes through the 200ns Leading Edge Blanking before reaching the Current Limit Comparator. When V_{CS} exceeds the internal threshold voltage V_{CSTH} , the Current Limit Comparator immediately turns off the Gate Driver via the PWM Latch. A Propagation Delay Compensation is added to the Current Limiting circuit to avoid excessive overshoot of the primary current, especially at the high line voltage (refer to chapter 10 Propagation Delay Compensation).

9. Leading Edge Blanking

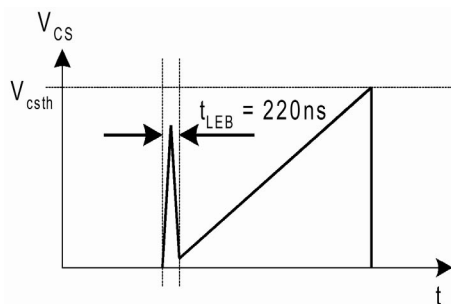


Fig.14. Leading Edge Blanking

Each time when the CoolMOS is switched on a leading spike is generated due to the

primary-side capacitance and secondary-side rectifier reverse recovery time (Fig. 14). This spike causes a premature turn-off of the Gate Driver if it exceeds the threshold voltage V_{CSTH} . To avoid it, the spike is blanked out with a time constant of $t_{LEB} = 220ns$. During the blanking time the Gate Driver can not be switched off by the Current Limit Comparator.

10. Propagation Delay Compensation

In case of overcurrent detection, that is when the sense voltage V_{CS} reaches the threshold voltage of the Current Limit Comparator V_{CSTH} , the shut down of the internal CoolMOS is delayed due to the propagation delay of the circuit between the current sense input I_{SENSE} and the Gate Driver output. This delay causes an overshoot of the peak primary current I_{PPEAK} . The overshoot is serious particularly at high input line voltage. Fig.15 shows an example of different current overshoots at two different line voltages. The example assumes that the primary inductance is $500\mu H$, the current sense resistor $R_{SENSE} = 1\Omega$, the propagation delay time $t_{PROP_DELAY} = 200ns$ and the input line voltages after rectification are $V_{1IN1} = 100V$ and $V_{1IN2} = 370V$.

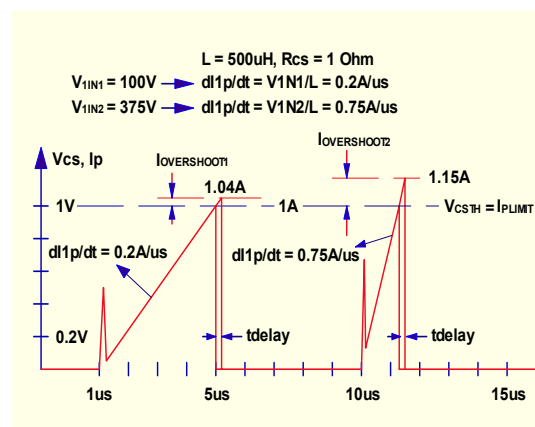


Fig.15. Current overshoot

The result of the example obviously shows that if the current sense threshold $V_{CSTH} = 1V$, the current overshoot $I_{OVERSHOOT2}$ at high line input voltage of $V_{IN2} = 375V$ and at $t_{DELAY} = 200ns$ is 15% higher than the actual current limit I_{PLIMIT} .

The Propagation Delay Compensation which is done by means of a dynamic voltage threshold V_{CSTH} as shown in Fig.16 is integrated in the IC to minimize the overshoot.

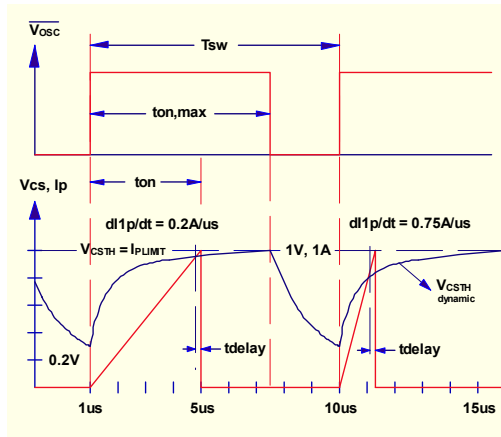


Fig.16. Dynamic Voltage Threshold V_{CSTH}

At high line input voltage, when the slope of the current sense voltage V_{CS} is steeper, the Gate Driver is switched off earlier due to the lower V_{CSTH} . The effect of the overshoot is then compensated.

The Propagation Delay Compensation in the IC is designed so that the tolerance of the internal current limiting is at $\pm 5\%$. The propagation delay time is compensated over temperature within a range of at least

$$0 \leq R_{CS} \times \frac{dI_P}{dt} \leq 1 \frac{dV_{CS}}{dt} \quad (4)$$

In this way, the IC is able to accurately limit the overcurrent (see Fig.17).

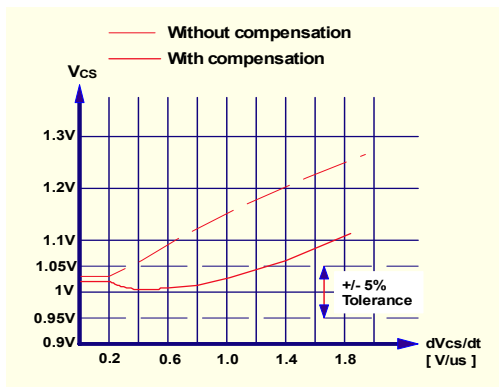


Fig.17. Overcurrent Shutdown

11. Protection Unit

An overload, open loop, overvoltage detection and a thermal shutdown are integrated within the Protection Unit (see Fig.1, Block Diagram). If the Protection Unit is activated, the Error Latch is set that disables the external power MOSFET after a blanking time of $5\mu s$. The blanking is used to avoid mistriggering of the Error Latch by voltage spikes during normal operation mode.

12. Overload + Open Loop with normal load and Auto Restart Mode

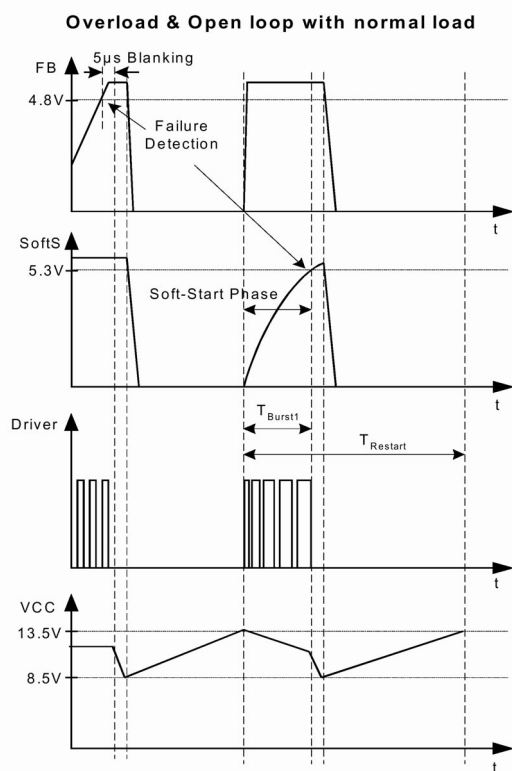


Fig.18. Auto Restart Mode

Fig.18 shows the Auto Restart Mode in case of overload or open loop with normal load. The detection of open loop or overload is provided by the Comparator C3, C4 and the AND-gate G2 (see Fig.19).

During operation at normal load the supply voltage of the IC V_{CC} is in the range of

8.5V and 13.5V, the Soft-Start voltage V_{SOFTS} is above 5.3V and the

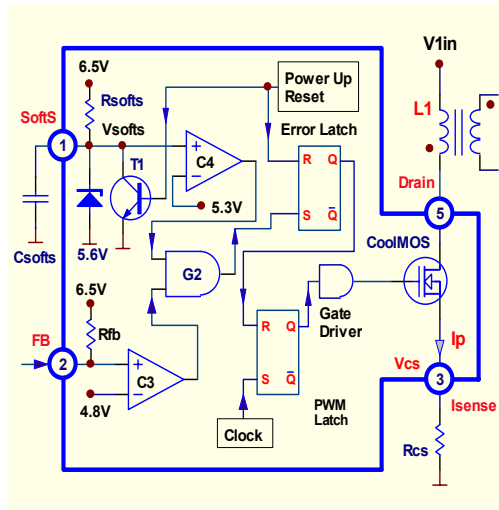


Fig.19. FB-Detection

feedback voltage V_{FB} stays lower than 4.8V. At this time the Comparator C_4 has released one of the input of the AND-gate G_2 . The comparator C_3 is now able to set the Error-Latch in case of open loop or overload, which leads the feedback voltage V_{FB} to rise above 4.8V. 5 μ s after the V_{FB} reaches the threshold voltage of 4.8V, the Gate Driver is terminated. The SMPS stops to operate which causes the supply voltage of the IC V_{CC} to drop. The IC is turned off when V_{CC} falls to $V_{CCoff} = 8.5V$. At this time the external soft-start capacitor C_{SOFTS} is discharged by the internal switch T_1 due to the Power Down Reset and the consumption current of the IC is reduced to maximum 55 μ A. The SMPS then goes into Auto Restart Mode. The V_{CC} increases again by charging the capacitor C_{VCC} through the Start-up Resistor $R_{START-UP}$ during the IC is inactive. When it reaches the turn-on threshold $V_{CCon} = 13.5V$, the IC is turned on again. The Error Latch is then reset by the Power Up Reset and the internal pull-up resistor R_{SOFTS} starts to charge the external Soft-Start capacitor C_{SOFTS} to start the Soft-Start Phase. During Soft-Start Phase the detection of overload and open loop by C_3 and G_2 is disabled by the Comparator C_4 . The Soft-Start Phase ends with the Soft-Start voltage $V_{SOFTS} \geq 5.3V$. If the overload or open loop failure is not removed after

the Soft-Start Phase, the Error Latch is activated and the SMPS goes into Auto Restart Mode again.

13. Overvoltage due to open loop with no load

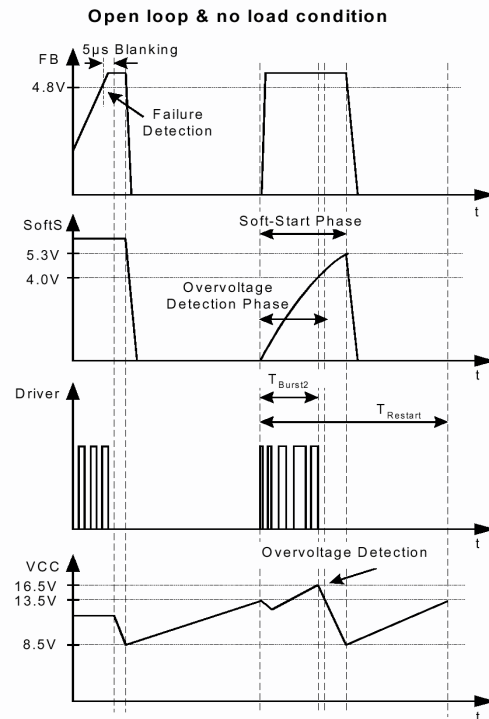


Fig.20. Auto Restart Mode

Fig.20 shows the Auto Restart Mode for open loop and no load condition. In case of this failure mode the SMPS output voltage as well as the V_{CC} increases. Additional comparators C_1 , C_2 and the AND-gate G_1 are implemented to detect this failure mode (see Fig.21).

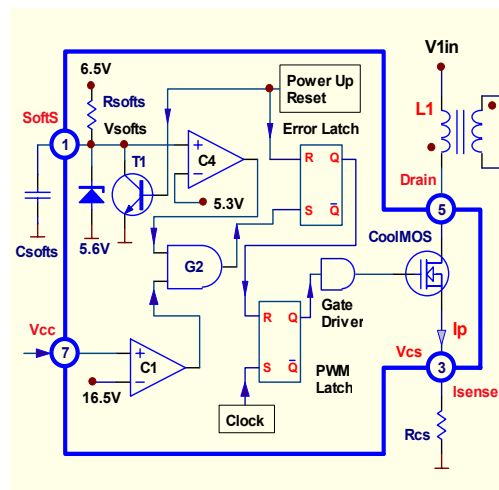


Fig.21. Overvoltage Detection

The overvoltage detection is provided by Comparator C1 only when the Soft-Start voltage V_{SOFTS} is below the threshold of the Comparator C2 at 4.0V and the voltage at pin FB is above 4.8V. During this overvoltage detection phase Comparator C1 can set the Error Latch and terminates the Burst Phase earlier during Auto Restart Mode when V_{CC} exceeds 16.5V. Once the Soft-Start phase is over, which means that the V_{SOFTS} is above 4.0V, the overvoltage detection by C1 is disabled. This will enable the V_{CC} to vary in the range of 8.5V to 21V caused by output load changes at normal operating mode.

14. 30W Demo Power Supply Board

Fig.22 shows a very simple and low cost 30W switching power supply circuitry utilizing the ICE2B265P. It is designed for used as the power supply of a Digital Photo Printer.

The specification of the circuits:

Input voltage range

85 – 265 V_{AC} 50/60Hz

Output

18V/1.67A

Maximum output power

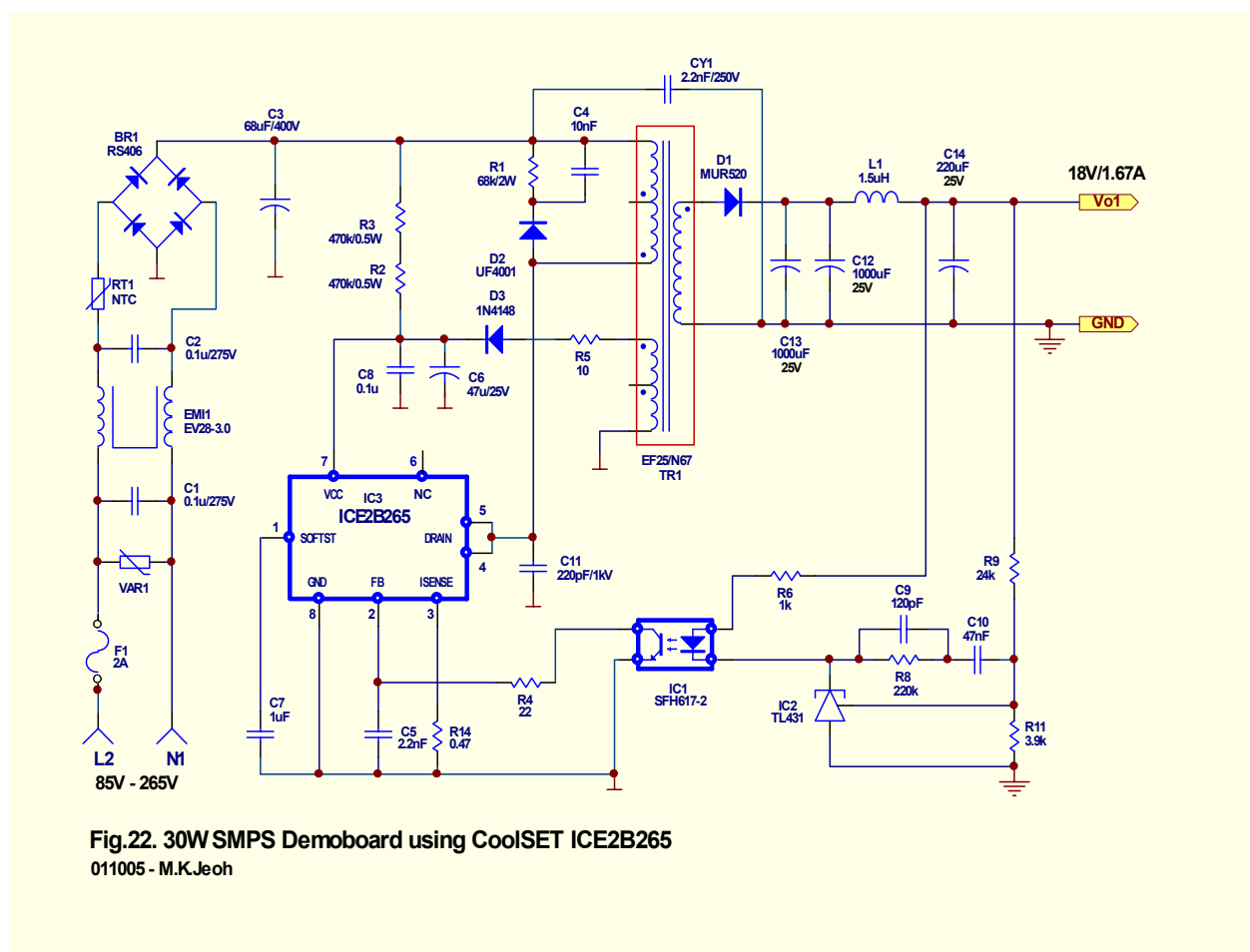
P_{OMAX} = 30W

Input power at standby mode

P_{IN} ≤ 0.5W at P_O = 0W and V_{IN} = 240Vac

Efficiency

η ≥ 80%



15. Design of the Power Supply

15.1. Determine input capacitor C_3 and minimum DC input voltage V_{1MIN}

To choose the value of the input capacitor C_5 the following rule of thumb is applied:

$C_5 = 2$ to $3 \mu F$ per W for 100/115V_{AC} or universal input.

$C_5 = 1 \mu F$ per Watt for 230V_{AC}.

$C_5 = 68 \mu F$ is selected for this design. The minimum DC input voltage V_{1MIN} (see Fig.24) at the lowest line voltage of 85V is a very important parameter for the calculation of the transformer. It can be obtained with good approximation by the following equations:

$$V_{1MIN} = \sqrt{V_{ACMIN,PK}^2 - \frac{2 \times W_{IN}}{C_5}} \quad (5)$$

$V_{ACMIN,PK}$ is the minimum peak input voltage, whereas W_{IN} is the energy which is discharged out of C_5 .

$$V_{ACMIN,PK} = V_{ACMIN} \times \sqrt{2} \quad (6)$$

The discharged energy W_{IN} is equivalent to the required peak output power P_{OPK} for the duration of the discharge time $T_L/2 - t_C$.

$$W_{IN} = \frac{P_{OPK}}{\eta} \times \left(\frac{T_L}{2} - t_C \right) \quad (7)$$

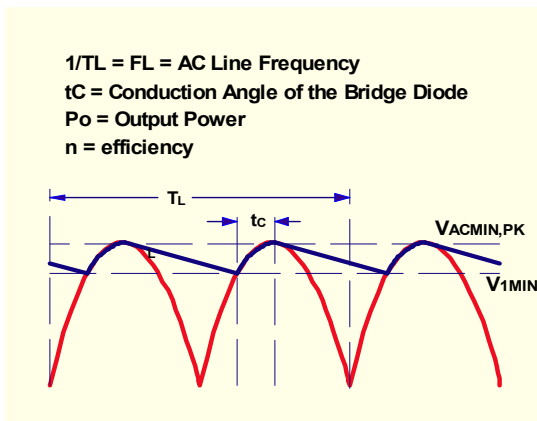


Fig.23 Input Voltage Ripple

Assuming that the conduction time of the bridge rectifier diodes is about 3 ms and substitute the specified values in (5), (6) and (7), we obtain:

$$V_{ACMIN,PK} = 85V \times \sqrt{2} = 120V \quad (8)$$

$$W_{IN} = \frac{30W}{0.8} \times \left(\frac{20ms}{2} - 3ms \right) \quad (9)$$

$$W_{IN} = 0.26Ws$$

$$V_{1MIN} = \sqrt{(120V)^2 - \frac{2 \times 0.26Ws}{68\mu F}} \quad (10)$$

$$V_{1MIN} = 82V$$

Taking the voltage drop at the bridge rectifier into consideration, the V_{1MIN} should then be:

$$V_{1MIN} = 80V.$$

15.2 Transformer Calculation

15.2.1. Maximum Duty Cycle

The transformer is designed so that the SMPS is operated in discontinuous current mode for the whole operating range.

The maximum duty cycle d_{MAX} at minimum input voltage V_{1MIN} is chosen as

$$d_{MAX} = 0.5 \quad (11)$$

15.2.2 Reflected Output Voltage

The reflected output voltage V_R is the reflected value of the secondary voltage across the primary winding. It can be obtained by the equation

$$V_R = \frac{d_{MAX}}{1 - d_{MAX}} \times (V_{1MIN} - V_{DS}) \quad (12)$$

The Drain-Source voltage V_{DS} of the internal CoolMOS is negligible due to the smaller $R_{DS(on)}$. V_R is then:

$$V_R = \frac{0.5}{1 - 0.5} \times 80V = 80V \quad (13)$$

15.2.3 Maximum Primary Peak and RMS Current

The maximum primary peak current I_{1PKMAX} is proportional to the maximum output power. It can be derived as follow:

$$I_{1PKMAX} = \frac{2 \times P_{OMAX}}{\eta \times V_{1MIN} \times d_{MAX}} \quad (14)$$

Substitute the known values of P_{OMAX} , V_{1MIN} , d_{MAX} and the efficiency η into (14), I_{1PK} becomes:

$$I_{1PKMAX} = \frac{2 \times 30W}{0.8 \times 80V \times 0.5} = 1.875A \quad (15)$$

The maximum primary RMS current can be calculated from $I_{1PK,MAX}$ and d_{MAX} :

$$I_{1RMS,MAX} = I_{1PK,MAX} \sqrt{\frac{d_{MAX}}{3}} \quad (16)$$

$$I_{1RMS,MAX} = 1.875A \sqrt{\frac{0.5}{3}} = 0.77A \quad (17)$$

15.2.4 Primary Inductance L_1

Primary inductance can be determined by the energy equation of the flyback transformer defined below:

$$L_1 = \frac{2P_{OMAX}}{\eta I_{1PK,MAX}^2 f} \quad (18)$$

f is the switching frequency of the SMPS which is around 67kHz.

$$L_1 = \frac{2 \times 30W}{0.8 \times 1.875^2 A \times 67kHz} \approx 320\mu H \quad (19)$$

15.2.5 Number of Primary turns

For this design, core size of EF25 is recommended due to its low cost and easy availability. For 67kHz operation, Epcos N67 material is a good choice.

In the discontinuous current mode operation, at switching frequency of 67kHz, the maximum flux density in the core B_{MAX} is usually limited by the core loss. To keep the loss in the core at acceptable level (see Epcos datasheet,

N67 Core loss vs frequency), $B_{MAX} = 0.2T$ is chosen for the calculation of the number of primary turns N_1 .

$$N_1 = \frac{L_1 \times I_{1PK,MAX}}{B_{MAX} \times A_{MIN}} \quad (20)$$

A_{MIN} is the minimum cross sectional area of the core. For EF25, $A_{MIN} = 51.5mm^2$.

$$N_1 = \frac{320 \times 2}{0.2 \times 51.5} \approx 60 \quad (21)$$

The required core gap L_{GAP} to achieve the primary inductance L_1 with the number of primary turns N_1 can be calculated by using the equation given in Epcos data book for "Ferrites and Accessories"

$$L_{GAP} = \left(\frac{L_1}{N_1^2 \times K_1} \right)^{\frac{1}{K_2}} \quad (22)$$

K_1 and K_2 are the core-specific constants. For EF25, $K_1=90$, $K_2=-0.731$ are specified in the datasheet. In the calculation L_1/N_1^2 has to be in the dimension of nH. The needed core air gap is then

$$L_{GAP} = \left(\frac{320 \times 10^3}{60^2 \times 90} \right)^{-0.731} mm \quad (23)$$

$$L_{GAP} = 1.02mm$$

15.2.6 Number of Secondary Turn

The number of turn for the secondary output can be derived from the reflected output voltage V_R in (13) and the number of primary turns N_1 . During the flyback time all windings will have the same volt per turn V_T :

$$V_T = \frac{V_R}{N_1} = \frac{80V}{60 \text{ turns}} = 1.33 \frac{V}{\text{turn}} \quad (24)$$

The number of turns N_{O1} for 18V-output V_{O1} is then:

$$N_{O1} = \frac{V_{O1} + V_D}{V_T} \quad (25)$$

V_D is the output diode forward voltage drop, which is typically about 1V.

$$N_{O1} = \frac{18+1}{1.33} \approx 14 \quad (26)$$

The bias voltage for the V_{CC} should be around 15V. The number of turn for the bias winding is then:

$$N_{BIAS} = \frac{V_{BIAS} + V_D}{V_T} = \frac{16}{1.33} \approx 12 \quad (27)$$

15.2.7 Output Rectifier Diodes

To select the proper output rectifier diode, the maximum peak inverse voltage across the diode $V_{D1,PK}$ has to be defined. $V_{D1,PK}$ can be obtained by the equation defined below:

$$V_{D1,PK} = V_{O1} + \left(\frac{N_{O1}}{N_1} \times V_{1MAX} \right) \quad (28)$$

whereas V_{1MAX} is the maximum DC input voltage. The calculation result is:

$$V_{D1,PK} = 18V + \left(\frac{14}{60} \times 375V \right)$$

$$V_{D1,PK} = 105.5V$$

The reverse voltage rating of the selected diode V_{DR} should be greater than 1.25x V_{DPK} and the rated DC current has to be at least 3 times the maximum output current. MUR520 is chosen for used in this design.

15.2.8 Maximum Secondary Peak and RMS Current

The maximum secondary peak and RMS currents are propotional to the maximum DC output current as follows:

$$I_{OPK,MAX} = \frac{2 I_{OMAX}}{1 - d_{MAX}} \quad (29)$$

$$I_{ORMS,MAX} = I_{OPK,MAX} \times \sqrt{\frac{1 - d_{MAX}}{3}} \quad (30)$$

I_{OMAX} is the maximum DC output current, $I_{OPK,MAX}$ is the maximum peak output current and $I_{ORMS,MAX}$ is the maximum RMS

output current. The results of the calculation is listed in Table 1.

Secondary Output	Max. Peak Current	Max. RMS Current
18V/1.67A	$I_{O1PK,MAX}$ 6.68A	$I_{O1RMS,MAX}$ 2.73A

Table 1. Max. Peak and RMS Output Current

15.2.9. Output Capacitors

Output capacitor selection is dominated by the R_{ESR} (equivalent series resistance) and the ripple current rating of the capacitor. The ripple current, which flows through the output capacitor, can be calculated as follows:

$$I_{O,RIPPLE} = \sqrt{I_{ORMS,MAX}^2 - I_{OMAX}^2} \quad (31)$$

The ripple current in the output capacitor of the 18V/1.67A will then be:

$$I_{O1,RIPPLE} = \sqrt{2.73^2 - 1.67^2} A$$

$$I_{O1,RIPPLE} = 2.16A \quad (32)$$

The Epcos datasheet of her B41858-series aluminum electrolytic capacitor shows that the rms current rating of a 1000μF/25V capacitor at 100kHz switching frequency and 105°C ambient is 1.69A. 2 pieces of this capacitors (Fig.22) have to be used to accommodate the required ripple current of V_{O1} . The R_{ESR} of these capacitors are specified as 0.034Ω. The output ripple voltage caused by the parallel of these two R_{ESR} , which is $R_{ESRTOT} = 0.017\Omega$, is then:

$$V_{O1,RP} = I_{O1PK,MAX} \times R_{ESRTOT}$$

$$V_{O1,RP} = 6.68A \times 0.017\Omega = 0.11V \quad (36)$$

This switching ripple voltage is further reduced by the additional L-C filter (L_3 and C_{14} in Fig.22). The 220μF/25V with $R_{ESR} = 0.12\Omega$ is chosen for C_{14} . To eliminate the pole in the control loop caused by the L_1 - C_{14} filter, L_1 has to be around 1.5μH. With this L_1 - C_{14} values combination, $V_{O1,RP}$ is reduced to:

$$\begin{aligned} V'_{O1,RP} &= V_{O1,RP} \times \frac{R_{ESR}}{2\pi f L_4 + R_{ESR}} \\ &= 0.11 \times \frac{0.12}{2\pi \times 67 \times 1.5 \times 10^{-3} + 0.12} \text{ V} \quad (34) \\ &\approx 18\text{mV} \end{aligned}$$

The switching ripple voltage $V'_{O1,RP}$ appears at the output terminal has been attenuated to around 18mV.

15.3 Current Sense Resistor

The current sense resistor (R_{14} in Fig.22) is defined by the maximum primary peak current and the minimum threshold voltage of the Current Limiting $V_{CSTHMIN}$.

$$R_{14} = \frac{V_{CSTHMIN}}{I_{PK,MAX}} = \frac{0.95\text{V}}{2\text{A}} \approx 0.45\Omega \quad (35)$$

Since the maximum loss occurred in R_{14} can be:

$$\begin{aligned} P_{R14MAX} &= I_{RMS,MAX}^2 R_{14} \\ P_{R14MAX} &= 0.765^2 \times 0.45\text{W} = 0.26\text{W} \end{aligned} \quad (36)$$

a 1W low inductance resistor is recommended.

15.4 Soft-start capacitor C_7

As mentioned in chapter 6 “Soft-Start” on page 4 and 5, the duration of the soft-start phase $T_{SOFT-START}$ has to be long enough to ensure proper start-up of the SMPS. That means V_{O1} has to be at 18V before V_{SOFTS} reaches 5.3V (see Fig.11 on page 5, $T_{SOFT-START} > T_{START-UP}$).

To estimate the $T_{START-UP}$, the available power during the soft-start phase, which charges the output capacitors, has to be defined. The total value of all capacitors at the output is:

$$C'_{O1} = C_{12} + C_{13} + C_{14} = 2220\mu\text{F} \quad (37)$$

In case of hard-start (if soft-start does not exists), the power which will charge C'_{O1} is:

$$P'_{O1} = \eta \times \frac{1}{2} \times L_1 \times f \times \left(\frac{V_{CSTHMIN}}{R_{14}} \right)^2 \quad (38)$$

$$\begin{aligned} P'_{O1} &= 0.8 \times \frac{1}{2} \times 320 \times 67 \times 10^{-3} \times \left(\frac{0.95}{0.45} \right)^2 \text{ W} \\ P'_{O1} &= 38.2\text{W} \end{aligned}$$

Assuming that the charge-up power to the C'_{O1} rises linearly during the soft-start phase, the charge power is then only half of 38.2W. $T_{START-UP}$, which is needed to raise the voltage V_{O1} to 18V, can then be estimated:

$$T_{START-UP} = \frac{1}{2} \times \frac{V_{O1}^2 \times C'_{O1}}{0.5 P'_{O1}} \quad (39)$$

$$T_{START-UP} = \frac{18^2 \times 2220}{38.2} \mu\text{s} \approx 18.8\text{ms}$$

In the application circuit of Fig.22, the external soft-start capacitor $C_7 = 1\mu\text{F}$ is recommended. The internal soft-start resistor $R_{SOFTS} = 50\text{k}\Omega$ is specified on the datasheet of the IC. The soft-start time $T_{SOFT-START}$ can then be calculated using (3):

$$T_{SOFT-START} = 1.69 \times 50 \times 1 \text{ ms} = 84.5\text{ms} \quad (40)$$

In this case, $T_{SOFT-START} > T_{START-UP}$ and the start-up of the SMPS is secured.

15.5 Capacitor at V_{CC} C_6

The V_{CC} capacitor C_6 (C_{VCC} in Fig.22) needs to ensure the power supply of the IC until the power can be provided by the auxiliary bias winding. Regardless the current transfer from the start-up resistor R_1 and the auxiliary winding during start-up time $T_{START-UP}$, the capacitance value C_6 can be estimated as below:

$$C_6 = \frac{I_{VCC3} T_{START-UP}}{V_{CCHY}} \quad (41)$$

I_{VCC3} is the IC supply current with active gate-drive. Its maximum value is 8mA as specified on the datasheet. $V_{CCHY} = 5\text{V}$ is the turn-on/off hysteresis of the IC supply voltage V_{CC} . Based on the estimated value of $T_{START-UP}$ in (39), C_6 should then be:

$$C_6 = \frac{8\text{mA} \times 18.8\text{ms}}{5\text{V}} \approx 30\mu\text{F} \quad (42)$$

$C_6 = 47\mu F$ is selected to sustain the V_{cc} .

15.6 Start-up Resistor R_2 and R_3

The start-up resistor $R_{\text{START-UP}}$ consists of R_2 and R_3 , which is connected in series as shown in Fig.22. By using (1) on page 2, the longest start-up delay time, which happens at the lowest line- input voltage $V_{\text{ACMIN}} = 85\text{V}$ can be estimated:

$$t_{\text{START-DELAY}} = \frac{C_6 V_{\text{CCON}}}{\frac{V_{\text{ACMIN}}\sqrt{2}}{R_{\text{START-UP}}} - I_{\text{VCC1}}} \quad (43)$$

$$t_{\text{START-DELAY}} = \frac{47\mu\text{F} \times 13.5\text{V}}{\frac{85\text{V}\sqrt{2}}{2 \times 470\text{k}\Omega} - 55\mu\text{A}} \approx 8.7\text{s}$$

In worst case, the IC is turned on only in 8.7s after the SMPS is plugged to the main line. The maximum loss occurs in $R_{START-UP}$ is roughly:

$$P_{ST-LOSS} \approx \frac{(V_{ACMAX}\sqrt{2})^2}{R_{START-UP}} \quad (44)$$

$$P_{ST-LOSS} = \frac{(265V\sqrt{2})^2}{2 \times 470k\Omega} \approx 0.15W$$

15.6 Control Loop Design

15.6.1 Power Stage Transfer Function

Fig. 24 shows the essential elements of the control loop.

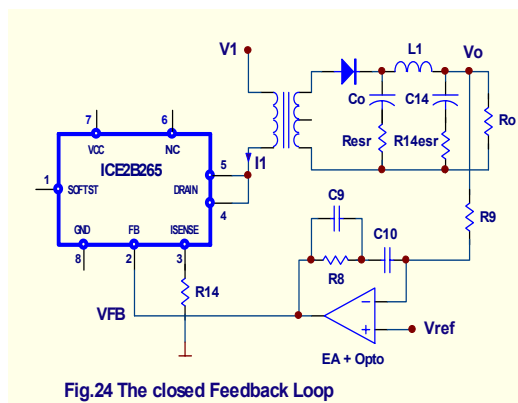


Fig.24 The closed Feedback Loop

Following equations are used to define the DC or low frequency gain of the feedback loop of the power stage (from the control voltage v_{FB} at the feedback-input pin2 to the output voltage node v_O):

$$P_O = \frac{1}{2} \times I_1^2 \times L_1 \times f \times \eta \quad (45)$$

$$P_0 = \frac{v_0^2}{R_0} \quad (46)$$

$$\frac{I_1}{v_{FB}} = \frac{V_{CSTH}}{R_{14} \times A_v} \quad (47)$$

Substitute P_0 and I_1 in (45) with (46) and (47) and rearrange the equation in term of v_0/v_{FB} , we obtain

$$G_{PS} = \frac{v_O}{v_{FB}} = \frac{V_{CSTH}}{R_{14} \times A_v} \times \sqrt{\frac{\eta L_1 R_{Of}}{2}} \quad (48)$$

A_v is the PWM-OP gain, which is equal to 3.65 as specified in the datasheet of ICE2B265. Equation (48) shows that the DC or low frequency gain G_{PS} of the power stage is proportional to the square root of the output load R_O and independent of the input voltage variation due to the current mode control. For $R_{O\min} = 10.8\Omega$ (at $P_{O\max} = 30W$), the minimum gain is

$$\begin{aligned} G_{PS,MIN} &= \frac{0.95}{0.45 \times 3.65} \times \sqrt{\frac{0.8 \times 320 \times 10.8 \times 67 \times 10^{-3}}{2}} \\ G_{PS,MIN} &= 5.6 \\ G_{PS,MIN} &= 14.9 \text{ dB.} \end{aligned} \quad (49)$$

In case of $P_{\text{OMIN}} = 0.5\text{W}$, the output load will be $R_{\text{OMAX}} = 648\Omega$, the maximum power stage gain will then be

$$\begin{aligned} G_{PS,MAX} &= \frac{0.95}{0.45 \times 3.65} \times \sqrt{\frac{0.8 \times 320 \times 648 \times 67 \times 10^{-3}}{2}} \\ G_{PS,MAX} &= 43 \\ G_{PS,MAX} &= 32.7 \text{ dB} \end{aligned} \quad (50)$$

The small signal transfer function of the power stage with its pole and ESR-zero is shown below:

$$\mathbf{G}_{PS}(s) = \mathbf{G}_{PS} \times \left[\frac{1 + sR_{ESR}C_O}{1 + s \frac{R_O}{2} C_O} \right] \quad (51)$$

C_o consists of C_{12} and C_{13} (see Fig.22) with the total value of $2000\mu F$ and R_{ESR} is the ESR values (see page 12) of both capacitor in parallel, Thus $R_{ESR} = 0.017\Omega$. The poles and zero at minimum and at maximum power are listed in Table 2 below:

Output Power	Poles $F_p = 1/\pi R_o C_o$	Zeros $F_z = 1/2\pi R_{ESR} C_o$
$P_{OMAX} = 30W$ $R_o = 10.8\Omega$	$F_{PH} = 14.7Hz$	$F_z = 4.68kHz$
$P_{OMIN} = 0.5W$ $R_o = 648\Omega$	$F_{PL} = 0.24Hz$	$F_z = 4.68kHz$

Table 2. Poles and zero

The transfer function of the output filter L_1 - C_{14} can be expressed as follows:

$$G_{LC} = \frac{1 + \frac{1}{sC_{14}R_{14ESR}}}{1 + s \left(\frac{L_1}{R_{14ESR}} - \frac{1}{\omega^2 C_{14}R_{14ESR}} \right)} \quad (52)$$

C_{14} and L_1 have to be selected so that the pole of the filter F_{PLC} is located far a way from the crossover frequency F_{CO} to avoid its influence in the control loop. The control loop bandwidth can only be kept high with high F_{PLC} , which is desirable. The L-C filter has a -2 gain slope with rapid changes of phase shift, which could induce instability in the control loop. To prevent it, the pole has to be compensated by the zero as mentioned on page 12. Based on this consideration, Epcos Al-capacitor B41858-series of $C_{14} = 220\mu F/35V$ with $R_{14ESR} = 0.084\Omega$ is selected. The zero frequency is then at:

$$F_{Z14} = \frac{1}{2\pi R_{14ESR} C_{14}} = 8.6kHz \quad (53)$$

Set the pole equal to zero and solve for the inductance L_1 :

$R_6=1k\Omega$ is chosen to limit the maximum current that flows into TL431. In order to achieve larger bandwidth and at the same time to get the overall gain response with -1 slope, the crossover frequency $F_C = 3kHz$ is selected. The gain of the power stage at F_C and at full load can then be derived from (51)

$$\frac{1}{2\pi\sqrt{L_1 C_{14}}} = 8.6kHz \quad (54)$$

$$L_1 = 1.55\mu H$$

With this combination of L_1 and C_{14} , the influence of the filter on the control loop can thus be neglected; the small signal transfer function of the power stage is then dominated only by (51).

The open loop gain and phase responses of the transfer function for the minimum and maximum output power are shown in Fig.26 and in Fig.27.

To close the loop, the feedback loop circuitry as shown in Fig.25 is added. It consists of a compensation network (TL431, $R_6 - R_{11}$, C_9 and C_{10}) and the optocoupler IC_2 .

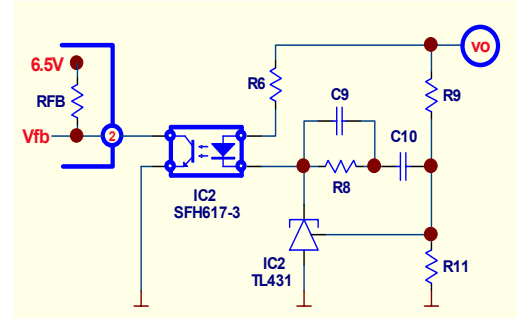


Fig.25 Feedback Loop Circuitry

The transfer function of the feedback loop is

$$G_{FB}(s) = \frac{V_{FB}(s)}{V_O(s)} = \frac{G_C R_{FB}}{R_6} \cdot \frac{1 + s(C_9 + C_{10})R_8}{sC_{10}R_9(1 + sC_9R_8)} \quad (55)$$

, where G_C is the current transfer ratio of the optocoupler. For SFH617-3, $G_C = 100\%$. The internal pull-up resistor at FB (pin2) is specified as $R_{FB} = 3.7k\Omega$.

$$|G_{PSH}(s)| = G_{PSMIN} \times \sqrt{\frac{1 + \left(\frac{F_C}{F_Z}\right)^2}{1 + \left(\frac{F_C}{F_{PH}}\right)^2}} \quad (56)$$

$$|G_{PSH}(s)| = 5.2 \times \sqrt{\frac{1 + \left(\frac{3\text{kHz}}{4.68\text{kHz}}\right)^2}{1 + \left(\frac{3\text{kHz}}{14.7\text{Hz}}\right)^2}} = 0.03$$

$$G_{PSH}(F_C) = -30.4\text{dB}$$

The feedback loop gain with TL431 has to be 30.4dB at F_C and must have zero slope response. For further calculation, R_9 has to be defined first. R_{11} determines the bias current of the resistor divider $R_9 - R_{11}$. If $R_{11} = 3.9\text{k}\Omega$ is selected, R_9 can be calculated by

$$R_9 = R_{11} \left(\frac{V_O}{V_{REF}} - 1 \right) \quad (57)$$

$$R_9 = 3.9\text{k}\Omega \times \left(\frac{18}{2.5} - 1 \right) = 24\text{k}\Omega.$$

V_{REF} is the reference voltage of TL431. To calculate the feedback loop gain at F_C , (55) can be simplified as below:

$$|G_{FB}(F_C)| = \frac{G_C R_{FB}}{R_6} \frac{R_8}{R_9} \quad (58)$$

Since $[G_{FB}(F_C)] = 30.4\text{dB}$,

$$R_8 = R_9 \times 10^{\frac{30.4}{20}} \times \frac{R_6}{G_C R_{FB}} \approx 200\text{k}\Omega \quad (59)$$

C_9 is obtained by placing the pole at $F_{PFB} = 2 \times F_C$.

$$C_9 = \frac{1}{2\pi R_8 F_{PFB}} = 133\text{pF} \quad (60)$$

In order to have sufficient phase margin, especially at light load, the zero is placed at $F_{ZFB} = 20\text{Hz}$. The value of C_{10} is then

$$C_{10} = \frac{1}{2\pi R_8 F_{ZFB}} - C_9 = 39\text{nH} \quad (61)$$

Based on above calculation, the values of the feedback network components are selected as follows:

$$R_8 = 220\text{k}\Omega$$

$$R_9 = 24\text{k}\Omega$$

$$C_9 = 120\text{pF}$$

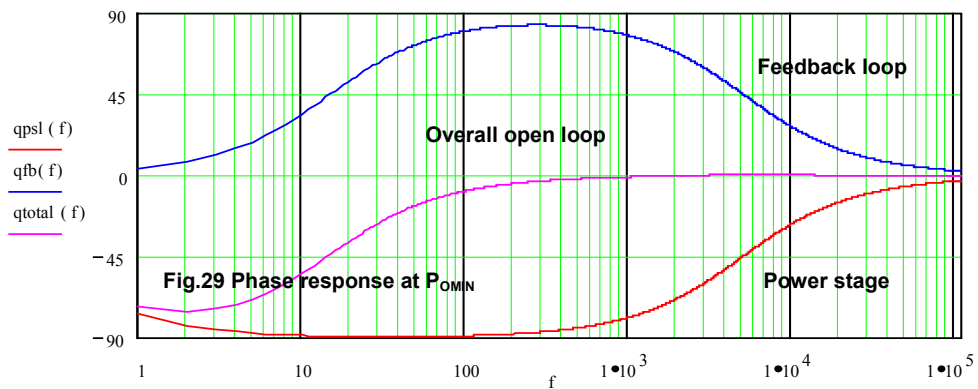
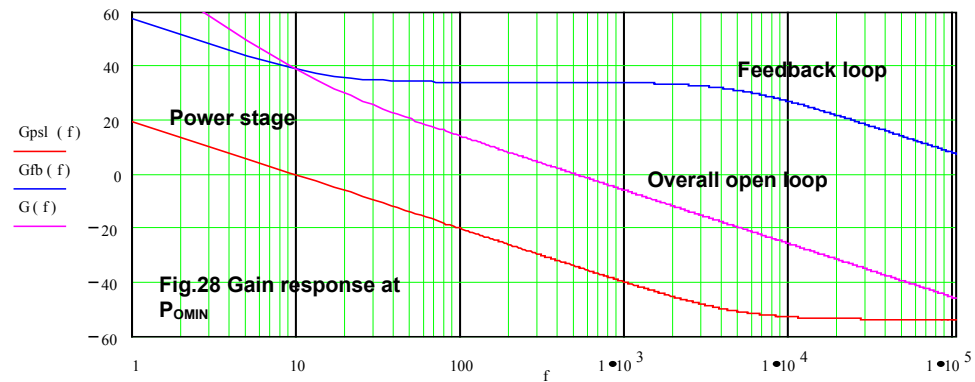
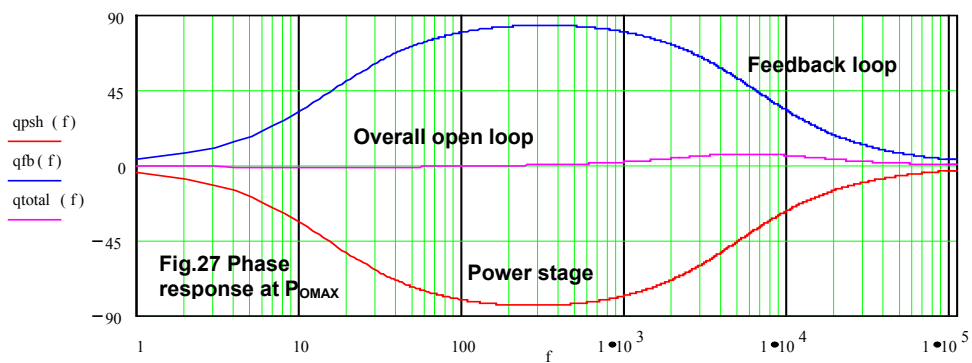
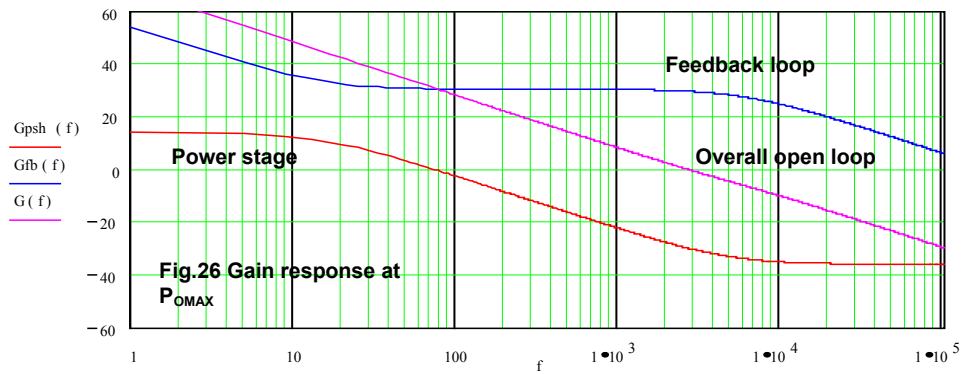
$$C_{10} = 47\text{nF}$$

$$F_{ZFB} = 15.4\text{Hz}, F_{PFB} = 6\text{kHz}$$

Fig.26 and Fig.28 also illustrate the responses of the feedback loop circuitry and the total open loop, whereas Fig.27 and Fig.29 show its respective phase responses.

16. Summary

This application note introduced briefly the features and functions of the CoolSET™, the new integrated product that includes PWM control IC and the CoolMOS™, the new generation Power MOSFET. A low cost 30W SMPS demo-board circuit is developed and its operation is analyzed in detail. The detail explanation of the board and the experiment results are described in the application note "30W Off-line SMPS Demoboard using CoolSET™ ICE2B265".



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