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Advantages of the Operational Amplifier Peripheral in PIC® Microcontrollers for SMPS Applications

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INTRODUCTION

Operational Amplifiers (op amps) are key components of all Switched Mode Power Supply (SMPS) solutions; they are used primarily in the feedback loop to either amplify the error signal – the difference between the set point and the output voltage. They also provide the gain and phase compensation required to maintain stability.

Most SMPS controllers have the op amp inside the IC, except for the offline dedicated controllers that use an external op amp and an optocoupler. The internal op amp has an internal fixed reference connected to the noninverting input and does not usually allow any connection or configuration changes. For applications that require more flexibility, extensive interconnection options might be needed. Several PIC® MCU families with integrated analog op amps can provide such flexibility, offering many internal signal pathways among all the analog peripherals. Besides the op amp, these parts have comparators, Pulse-Width Modulation (PWM) generators and slope compensation.

This technical brief describes how the op amp peripheral in the PIC16F176X/7X can be used to obtain a more flexible SMPS application, and how it can be connected internally with other Core-Independent Peripherals (CIPs) such as the Digital-to-Analog Converter (DAC) or First Voltage Reference (FVR) to obtain special functions.

Microcontrollers with CIPs

The PIC16F176X and PIC16F177X are microcontrollers (MCUs) with analog and digital peripherals that can be used to build a SMPS.

These peripherals run independently of any core supervision, hence the name Core Independent Peripherals (CIPs). They can be interconnected internally by means of a robust network of digital and analog multiplexers that provide great design flexibility.

MCU devices differ in pin count and available CIP. For example, the PIC16F1769 has two op amps and the PIC16F1779 has four op amps available, and both have the CIPs needed to build multiple channels of SMPS controllers. The operational amplifier found in the PIC16F176X/7X family has parameters similar to the Error Amplifier found in many SMPS ICs. See Table 1 for a direct comparison with popular models.

TABLE 1: PARAMETERS OF PIC16F176X/7X AND OTHER SMPS ICs

IC	PIC16F176X/7X	UCC3803	“3843” Architecture	“3842” Architecture
GBW	2 MHz	2 MHz	1 MHz	Not provided
Open Loop Voltage Gain	90 dB	60 - 80 dB	65 - 90 dB	65 - 90 dB
PSRR	80 dB	Not provided	60 - 70 dB	60 - 70 dB
Input Common-Mode Voltage	0 - V_{DD}	1.95 - 2.05V	2.42 - 2.58V	2.42 - 2.58V

IMPROVEMENTS OF THE CIP OPERATIONAL AMPLIFIER

The following chapter shows how the CIP Operational Amplifier can be used to improve the design of a standard or smart SMPS design. The envisioned topics are: the range of accepted signals, current sense offset capabilities, the error voltage scaling and the possibility to change the value of the voltage reference.

Range of Signals

For an SMPS design, the op amp typically has only a limited range of common-mode voltages. The CIP solution has a rail-to-rail common-mode voltage range. When a reference voltage is applied to the input of the error amplifier and it is used to control the output voltage, the common-mode characteristic of the op amp becomes critical.

ASIC solution: Most SMPS ICs present a common-mode voltage of 200 mV to 1V, which limits considerably the range of the reference voltages.

For example, the feedback error op amp from the “3843” architecture ICs has a common-mode voltage range of 0.4V (from 2.3V to 2.7V), set by the fixed feedback reference of 2.5V. The op amp is forced to work in a limited range because the internal reference cannot be changed. The output signal of the op amp is divided and limited to 1V, which limits current sense signal to a smaller range.

The “3842” architecture also has a fixed feedback reference of 2.5V. A slight variation is seen in the MAX17597, that has the reference to 1.21V and the common-mode voltage ranges from 1V to 1.75V. The LTC3803 has a lower reference (0.8V), but the level of the allowed signal is decreased.

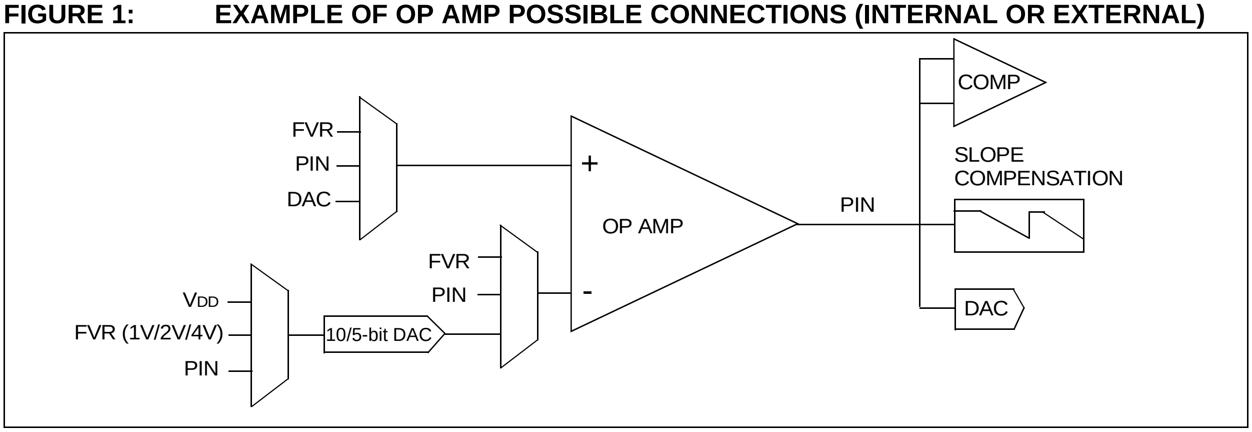
CIP solution: This is seen as a flexibility limitation that the op amp in the PIC® MCU overcomes. If the designer uses a current transformer or other measurement method that provides a larger current waveform (2V-4V) to improve accuracy and resolution, the PIC MCU solution can accommodate this requirement.

These observations show that legacy SMPS IC controllers are a good solution when these limitations do not affect the purpose of the application, while the PIC MCU solution overcomes all limitations.

The op amp has a better Signal-to-Noise Ratio (SNR) when the common-mode voltage range limit is increased to 0.4V - 5V. This allows the PIC MCU to operate with higher signal levels, reduce the effect of noise on the system, add offsets, and change the reference. These configurations make the solution flexible, smarter and more stable.

Another advantage that the CIP op amp has is the possibility to bring the input and output to external pins and/or connect them internally with other CIPs. CIPs can be enabled or disabled as required. Internal connections to DACs, FVR and Slope Compensation are possible to both the inverting or noninverting inputs; other peripherals can be connected through external pins. By connecting the output of the op amp to a 5-bit/10-bit DAC, the user can divide the signal. Another 10-bit DAC can be connected internally to either of the two op amp inputs as a variable reference. This offers control to the user over the output voltage value. The DAC can have the following voltage sources: the V_{DD} of the MCU, internal fixed voltages of 4V/2V/1V or even an external PIN. Figure 1 depicts the flexibility of the op amp CIP in the PIC MCU.

FIGURE 1: EXAMPLE OF OP AMP POSSIBLE CONNECTIONS (INTERNAL OR EXTERNAL)



Capability to Offset the Current Sense Waveform

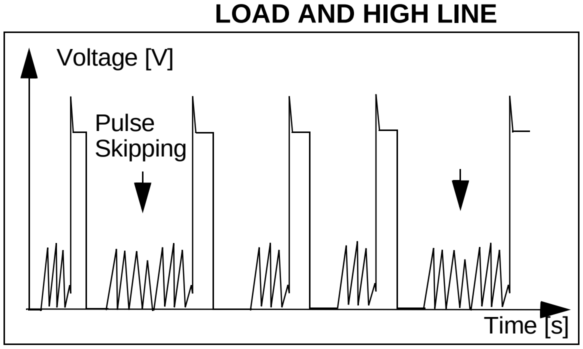
The comparator is an important component in a SMPS loop, but when both input signals are 0V or very close to 0V, it creates output uncertainty. The output uncertainty of the comparator will cause jitter, output voltage overshoots and pulse skipping of medium duty cycle pulses.

The capability to offset the current sense signal is needed to prevent the inputs of the comparators being 0V or close to 0V at the same time.

ASIC solution: Many legacy ASICs leave this problem unsolved and some address this problem with fixed internal offset. For example, the “3843” architecture does not have internal signal offset capabilities, but it is possible to generate an offset using the external VREF pin. The VREF pin is also used to generate the switching frequency signal, and the slope compensation, so this method can create a noise cycle. The MAX17597 brings an internal offset of 0.9V which solves the problem, but the peak CS signal level limits at 305 mV.

In Continuous Conduction mode, the inductor current does not hit 0 mA, so the Current Sense (CS) voltage signal does not hit the 0V level, but can go close to 0V, which still represents an issue. In Critical Conduction mode (Boundary Conduction mode) and Discontinuous Conduction mode the 0V level on the CS signal is hit on every cycle. This issue occurs often at Light Load and High Line condition, as depicted in Figure 2.

FIGURE 2: MEDIUM-HIGH DUTY CYCLE PULSE SKIPPING OPERATION AT LIGHT LOAD AND HIGH LINE

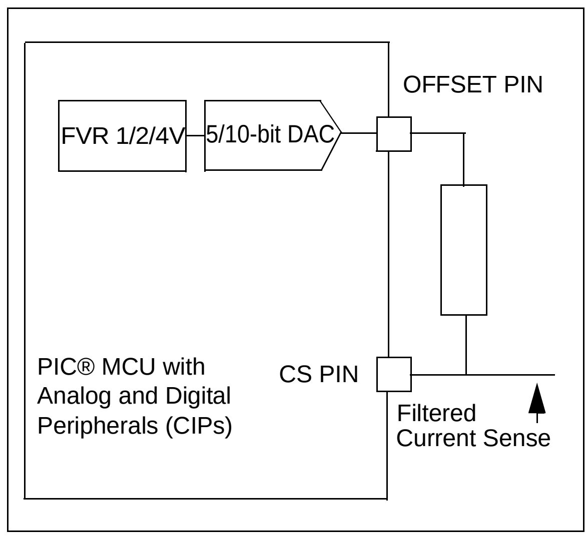


If the duty cycle is 5-15% when this issue happens, the pulse skipping can generate frequencies in the audio region.

Pulse skipping is an issue when the skipped pulse has a high duty cycle (>5%). When the minimum duty cycle goes lower than 2-3% and an open-circuit condition happens, then the pulse skipping will help maintain the output voltage constant and within the specified ripple. Another option to maintain the output voltage under a specified limit is to use a hysteretic control, though this will considerably increase the output voltage ripple. With the duty cycle being close and less than 1%, the frequency division created by the pulse-skipping operation has less chances to hit the audio frequencies and the circuit will maintain output stability. The ability to have small duty cycle helps solve the audio frequency switching issue, but this does not solve the comparator output uncertainty issue. The suggested solution is to add an offset voltage to the CS signal in order to shift the input signals to a higher level.

CIP solution: The PIC MCU with analog and digital peripherals (PIC16F176X/7X) can use the internal FVR that ensures good stability and accuracy even with VDD noises and temperature. The FVR can power the DAC and create various offset levels that can be controlled at any time by the user. This solution creates a reliable and jitter-less solution for the 0V comparison problem, as depicted in Figure 3. Adding the offset does not create any limitation for the CIPs because the input common-mode voltage of the comparator and op amp are rail-to-rail. The logic in the PIC MCU has also a dead-band and blanking function to eliminate turn-on spikes influence. All these advantages would not be possible without the flexibility of the CIP op amp.

FIGURE 3: THE FVR AND DAC CREATE A STABLE AND CONTROLLABLE OFFSET VOLTAGE



Error Voltage Scaling

Besides working with high-level signals, the SMPS IC must also be able to take small current signals. To do this easily, the op amp must be able to scale the error feedback signal to a smaller signal.

ASIC solution: Current and classic solutions have the ability to divide and limit the error signal, but in most cases it is a fixed ratio, with no option to disable the scaling.

For example, the “3843” architecture ICs scales the error voltage signal using internal diode and resistor series with a Zener diode to limit the upper end, as depicted in Figure 4.

The MAX17597 SMPS IC offers a division of the feedback error signal by two non-configurable signals. The LTC3803 does not offer internal scaling and the typical current signal is set to 100 mV.

CIP solution: The PIC® microcontroller with CIPs solution provides the ability to use the full error signal or to add scaling and obtain small signals.

In this case, the error feedback signal can be passed through a DAC and can be scaled down in 32 or 1024 steps using the 5- or 10-bit resolution. The scaling down solution using CIPs is depicted in Figure 5. The solution allows for the signal to be left intact or scaled to any proportion from 100% to 0.1% in steps of 0.1%. This solution allows for a very small signal comparison and the offset can still be used on the CS signal. This feature is possible because the internal op amp CIP allows access to all its pins.

FIGURE 4: FEEDBACK ERROR SIGNAL SCALING IN “3843” ARCHITECTURE ICS

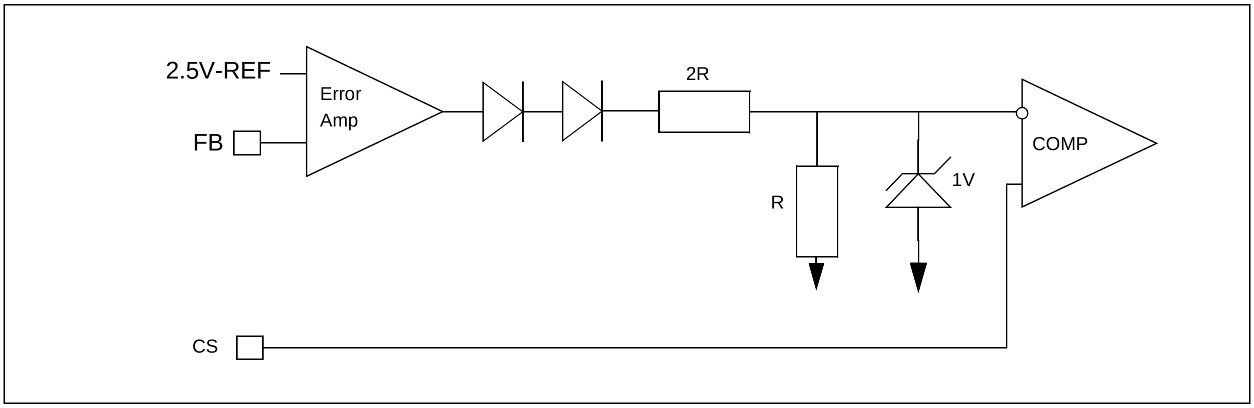
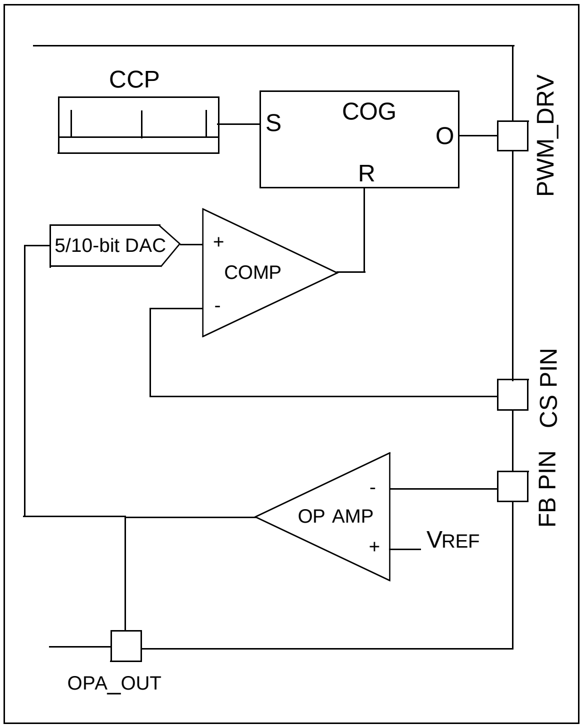


FIGURE 5: FEEDBACK ERROR VOLTAGE SCALING USING ONE OF THE DACs



Changing the Internal Voltage Reference

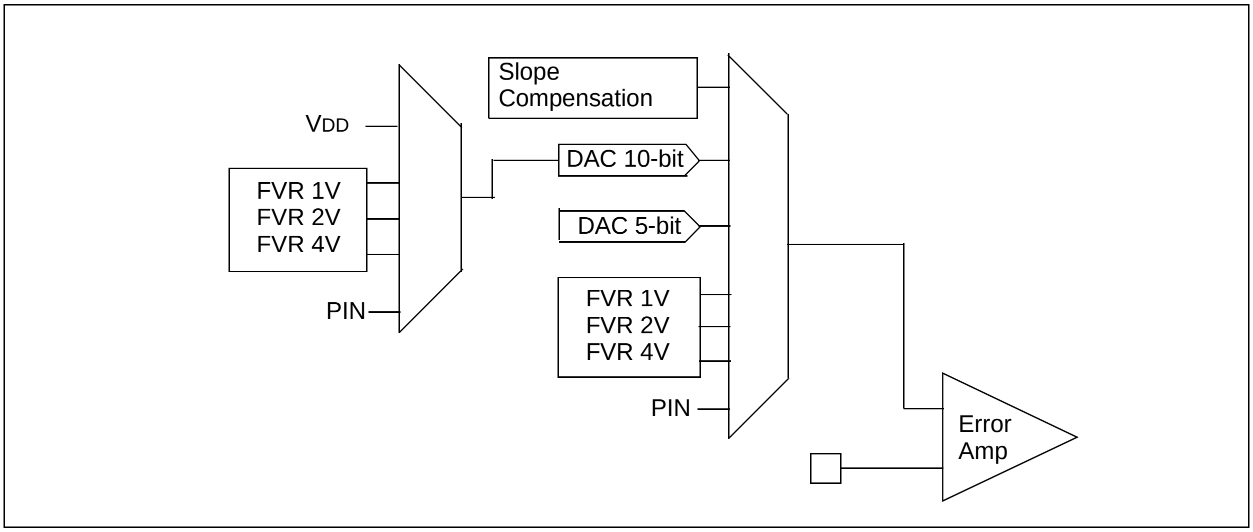
For a SMPS loop control, the op amp needs an accurate and stable voltage connected to the positive input that works as a reference. The reference will be compared to a portion of the output voltage connected to the negative input of the op amp and the difference will be amplified to generate the error signal. The voltage reference can be fixed or variable. When a SMPS controller with a Fixed Voltage Reference is used, the output voltage is usually constant and can be changed only by modifying the resistor divider values. A SMPS controller with a variable reference can change the output voltage value using the reference value.

ASIC solution: SMPS IC have a fixed internal voltage reference that is used as error amplifier positive input to generate error feedback voltage. The SMPS controllers dedicated for offline application are usually placed on the “hot” side and the error voltage is received through the isolation barrier with the help of an optocoupler and a fixed stable reference, so they do not have an internal op amp. To regulate the desired output voltage, the designer has to use a resistive divider to bring the output voltage to the same level. For example, the “3843” architecture has a fixed 2.5V internal reference that does not allow any configuration or modification. The change in resistor values or the potentiometer solution can be used only for small output variations (to adjust a drift of -0.5V to +0.5V in the desired output voltage). If this solution is used for higher output levels change (for example from 5V to 12V), then the designer has to change all the compensation components to fight instability. Another issue with Fixed Voltage Reference is that output values lower than 2.7V cannot be regulated. MAX17597 has an internal fixed reference of 1.21V and LTC3803 has a Fixed Voltage Reference of 0.8V, which allows the minimum regulated output voltage to be smaller, still offering no internal control.

CIP solution: SMPS controllers with a Fixed Voltage Reference work fine for fixed voltage output, but designers still use potentiometers to adjust the output voltage correctly, since component tolerances and temperature impact the divider result.

The PIC16F176X/7X family can use either a Fixed Voltage Reference or a pass through a DAC to change the reference value at any time. This approach allows the designer to adjust the output voltage without any physical modifications, taking into consideration the temperature effect on the components, as the PIC MCU is equipped with an on-chip temperature sensor. The adjustment of the output through the internal reference does not change the compensation poles and zeroes, and allows for an efficient and stable adjustable system. The fact that the DAC can change sources on the go allows using the 4V, 2V or 1V of the FVR. The 10-bit DAC has 1024 steps that can be used, so the reference value can be changed from 100% to 0.1% with 0.1% steps, and the output of the SMPS can be controlled without changing external components. If a more precise reference is needed, the DAC can have as input one of the I/O pins. Figure 6 illustrates how the internal connections are made to control the reference of the op amp. Internally, the DACs can be linked with comparators and create limits that shut down the circuit or implement some functions: hiccup operation, sleep and dependency functions.

FIGURE 6: ALLOWED INTERNAL CONNECTIONS FOR A REFERENCE TO THE ERROR AMPLIFIER



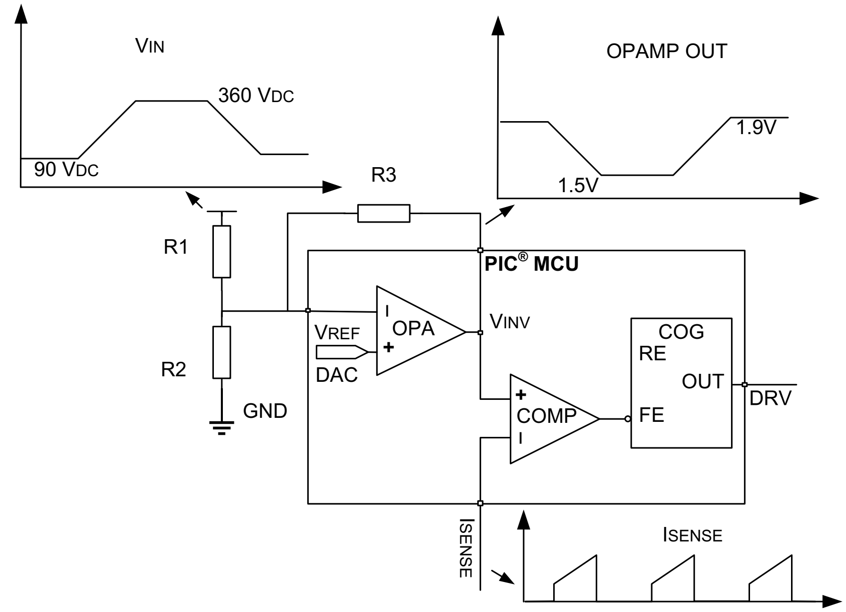
EXAMPLE OF OP AMP FLEXIBILITY AND CONFIGURATION ADVANTAGES

For a SMPS that admits a high variation of input voltage (e.g.: 85V-265V) and has the requirement of isolation, implementing an overcurrent protection circuit becomes complex.

The classic solution is to measure the output current and use an isolation IC (optocoupler or digital isolator) to transmit the information to the primary side of the SMPS controller.

A solution using the flexibility advantage of the op amp in the PIC MCU eliminated all the problems and required only three external resistances as depicted in Figure 7.

FIGURE 7: PEAK CURRENT LIMIT ADAPTABLE WITH THE CHANGE OF THE INPUT VOLTAGE USING THE INTERNAL CONFIGURABLE OP AMP OF THE PIC® MCU



This solution limits the total peak power delivery of the converter to the secondary. It also adapts with the change of input voltage and makes overcurrent protection easy.

It is possible to implement this solution thanks to the flexibility and configuration capabilities that the op amp CIP and other CIPs have in the PIC MCU SMPS solution.

For more information on this solution refer to the *Primary Side Offline Power Limiter Technical Brief* (DS90003160) on www.microchip.com.

CONCLUSION

As seen in the previous sections, the integration of a good quality operational amplifier module among the many core independent peripherals offered by the PIC16F176X/7X family of microcontrollers presents many advantages over the standard issue – fixed function – op amps present in legacy SMPS ICs.

The wide input range, high SNR, gain, flexible internal connection options for reference inputs and signal output scaling, contribute in making the SMPS integrated microcontroller solution a superior choice.

These add to the advantages of communication and run-time reconfiguration (adaptive) that are significant in such a device. In fact, the sum of all such features makes the PIC16F176X/7X family the ideal choice for the most challenging SMPS needs of modern smart embedded control applications.

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