Design Consideration with AP3005

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1. Introduction

The AP3005 is a 420kHz fixed frequency PWM buck (step-down) DC-DC converter, capable of driving a 2A load with high efficiency, low ripple and excellent line and load regulation. The device includes a voltage reference, an oscillation circuit, an error amplifier, an internal PMOS and etc.

The PWM control circuit is able to adjust the duty ratio linearly from 0 to 100%. The enable function, an over current protection function, a short circuit protection function and a soft-start function are built inside. When OCP or SCP happens, the operation frequency will be reduced from 420kHz to 40kHz. An internal compensation block is employed to minimize external components.

The AP3005 serves as ideal power supply units for portable devices, especially for chip set power in portable systems. It's widely used for PDVD audio and chip set power, LCD monitor, LCD TV chip set power and DPF chip set power.

2. General Description

The AP3005 series are monolithic IC designed for a step-down DC/DC converter, and own the ability of driving a 2A load without additional transistor. It saves board space. The external shutdown function can be controlled by logic level and then come into standby mode. The output of the Error Amplifier integrates the voltage difference between the feedback and the 0.8V bandgap reference. The polarity is such that an FB pin voltage less than 0.8V increases the COMP pin voltage. Since the COMP pin voltage is proportional to switch duty cycle, an increase in its voltage increases the power delivered to the output. Regarding protected function, thermal shutdown is to prevent over temperature operating from damage, and current limit is against over current operating of the switch. If current limit function occurs and V_{FB} is down below 0.52V, the switching frequency will be reduced. The AP3005 series operates at a switching frequency of 420kHz thus allow smaller sized filter components than what would be needed with lower frequency switching regulators. Other features include a guaranteed ±2% tolerance on output voltage under specified input voltage and output load conditions.

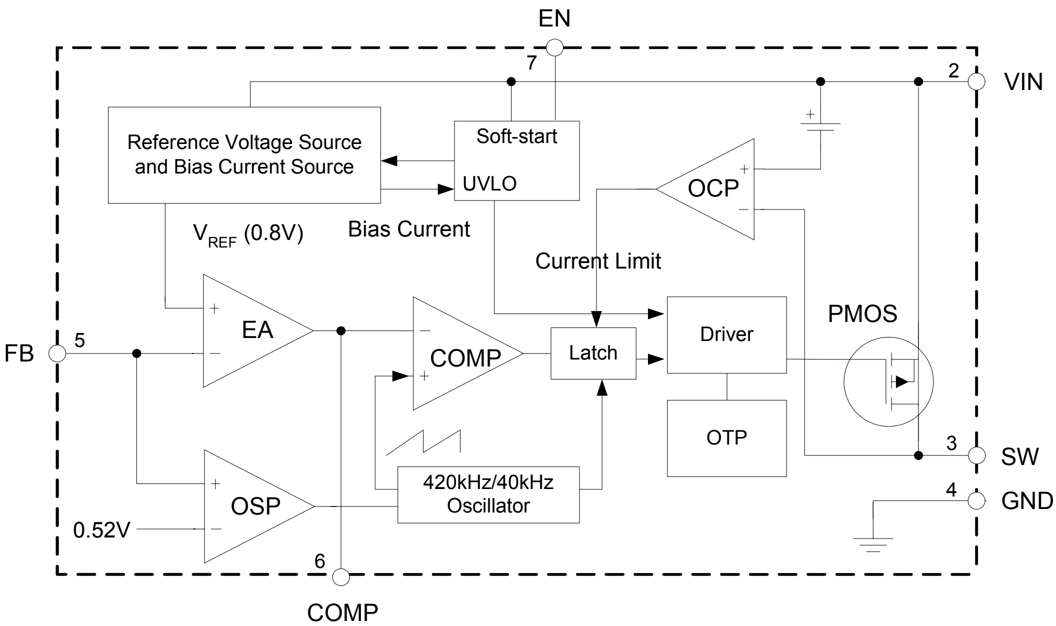

Figure 1. Functional Block Diagram of AP3005

2.1 Enable and Soft Start
The AP3005 has internal soft start feature to limit in-rush current and ensure the output voltage ramps up smoothly to regulation voltage. In soft start process, the output voltage is ramped to regulation voltage in typically 1ms. The 1ms soft start time is set internally.

The EN pin of the AP3005 is active high. The voltage on EN pin must be above 1.5V to enable the AP3005. When voltage on EN pin falls below 0.5V, the AP3005 is disabled. The quiescent current during shutdown is approximately 44μA (typ.).

2.2 Maximum Duty and Dropout
The AP3005 uses a P-Channel MOSFET as the high side switch. It saves the bootstrap capacitor normally seen in a circuit which is using an NMOS switch. It allows 100% turn-on of the upper switch to achieve linear regulation mode of operation. The minimum voltage drop from V_{IN} to V_{OUT} is the load current times DC resistance of MOSFET plus DC resistance of buck inductor. It can be calculated by equation below:

$$V_{OUT\_MAX} = V_{IN} - I_{OUT} \times (R_{DSON} + R_{L\_DCR})$$

Where V_{OUT_MAX} is the maximum output voltage, V_{IN} is the input voltage from 4.75V to 25V, I_{OUT} is the output current from 0A to 2A, $R_{DS(ON)}$ is the on resistance of internal MOSFET, the value is typical 130mΩ depending on input voltage and junction temperature, And R_{L_DCR} is the inductor DC resistance.

2.3 Switching Frequency
The AP3005 switching frequency is fixed and set by an internal oscillator. The actual switching frequency could range from 336KHz to 504KHz due to device variation

2.4 Over Current Protection (OCP)
The AP3005 has internal short circuit protection to protect itself from catastrophic failure under output short circuit conditions. The FB pin voltage is proportional to the output voltage. Whenever FB pin voltage is below 0.52V, the short circuit protection circuit is triggered. As a result, the converter is shut down and operating frequency reduces to 40KHz. The converter will start up once the short circuit condition disappears.

2.5 Thermal Protection
An internal temperature sensor monitors the junction temperature. It shuts down the internal control circuit and high side PMOS if the junction temperature exceeds 155°C. The regulator will restart automatically under the control of soft start circuit when the junction temperature decreases to 135°C.

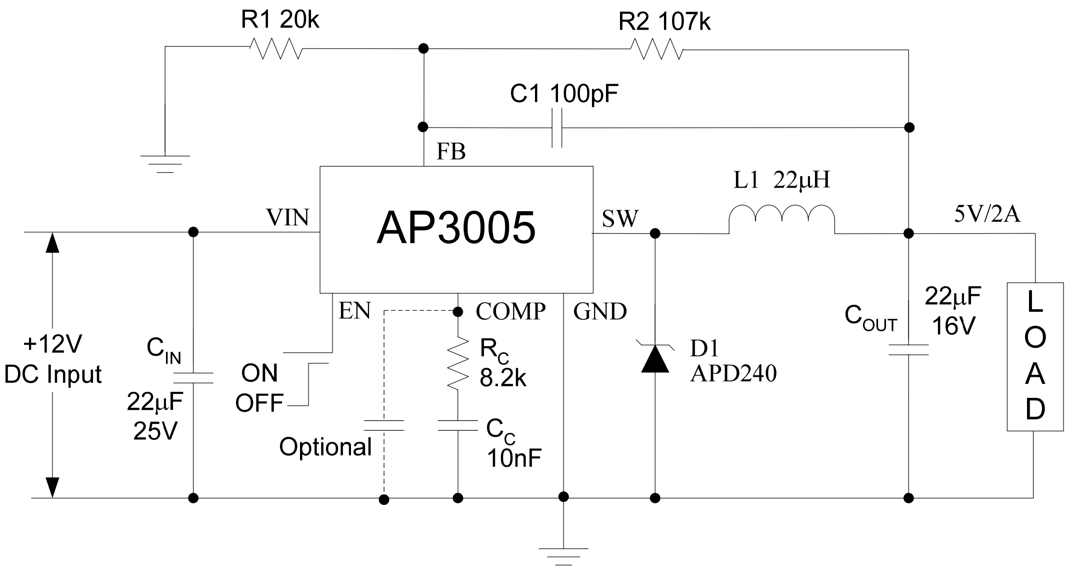

Figure 2. Typical Application 1 of AP3005 Applied with Ceramic Input and Output Capacitors

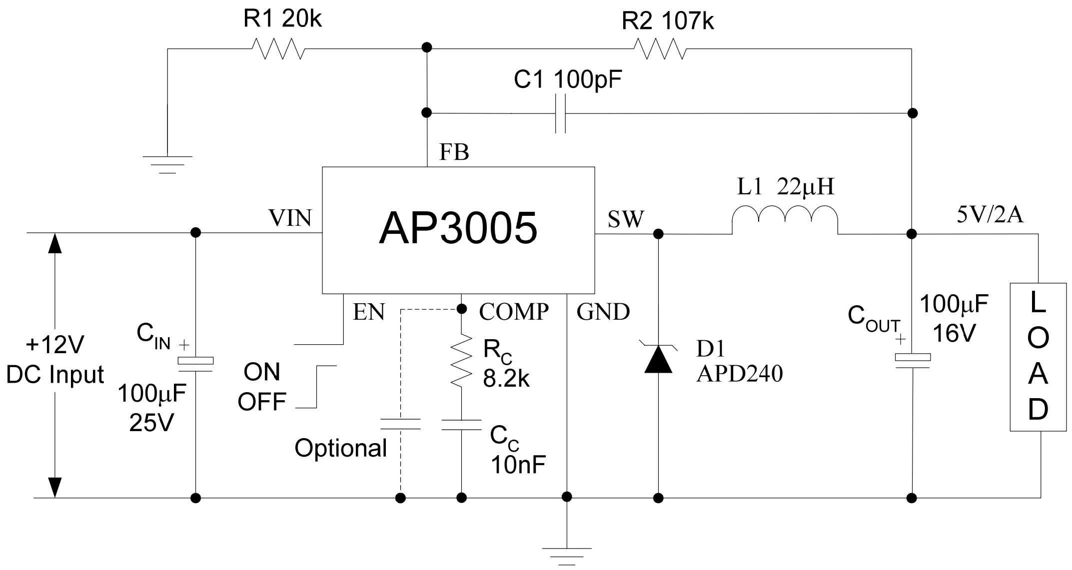

Figure 3. Typical Application 2 of AP3005 Applied with Electrolytic Input and Output Capacitors

3. Application Information

3.1 Setting the Output Voltage

The output voltage is set using a resistive voltage divider from the output to FB (see Figure 2). The voltage divider divides the output voltage down by the ratio:

$$V_{FB} = V_{OUT} \times \frac{R_1}{R_1 + R_2}$$

Where V_{FB} is the feedback voltage and V_{OUT} is the output voltage.

Thus the output voltage is:

$$V_{OUT} = 0.8 \times \frac{R_1 + R_2}{R_1}$$

First, select a value for R1, the recommended value is 20kΩ. The value of R1 can not be selected too high, because the higher resistor value makes the sensitive feedback pin prone to noise injection. Then, solve for R2:

$$R_2 = R_1 \times \left(\frac{V_{OUT}}{0.8} - 1 \right)$$

For example, for a 5.0V output voltage, R1 is 20kΩ and R2 is 105kΩ. Due to tolerance, we are selecting R2 is 107kΩ.

V_{OUT}	R_1	R_2
0.8	20K	0
1.2V	20K	10K
1.5V	20K	17.8K
1.8V	20K	25.2K
2.5V	20K	43K
3.3V	20K	62K
5.0V	20K	107K
9V	20K	205K
12V	20K	280K

Table1. Output Voltage vs. FB Resistor

3.2 Output Capacitor - C_{OUT}

The output capacitor is the most critical component of a switching regulator, it is used for output filtering and keeping the loop stable.

The primary parameters for output capacitor are the voltage rating and the equivalent series resistance (ESR) at 100kHz frequency. This capacitor voltage rating should be greater than 1.5 times of the maximum output voltage. The ESR value has relation to the voltage rating. For the same product series, the capacitor with higher voltage rating will have smaller ESR value (Figure 4). The ESR value is the most important parameter because it directly affects the system stability and the output ripple voltage. Ceramic, tantalum or low ESR electrolytic capacitors are recommended.

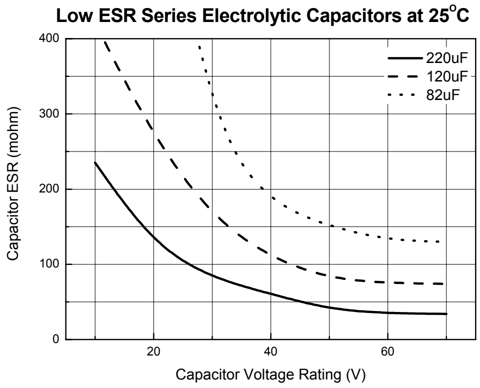

Figure 4.Capacitors ESR vs. Capacitor Voltage Rating

When low ESR ceramic capacitor is used as output capacitor, the impedance of the capacitor at the switching frequency dominates. Output ripple is mainly caused by capacitor value and inductor ripple current. The output ripple voltage calculation can be simplified to:

$$V_{Ripple} = \Delta I_L \times \left(R_{CO\_ESR} + \frac{1}{8 \times f \times C_{OUT}} \right)$$

For lower output ripple voltage across the entire operating temperature range, X5R or X7R dielectric type of ceramic, or other low ESR tantalum capacitor or aluminum electrolytic capacitor may also be used as output capacitors.

In a buck converter, output capacitor current is continuous. The RMS current of output capacitor is decided by the peak to peak inductor ripple current. It can be calculated by:

$$I_{CO\_RMS} = \frac{\Delta I_L}{\sqrt{12}}$$

Usually, the ripple current rating of the output capacitor is a smaller issue because of the low current stress. When the buck inductor is selected to be very small and inductor ripple current is high, output capacitor could be overstressed.

A low ESR aluminum electrolytic or solid tantalum capacitor is preferred to keep the output voltage ripple low. The output ripple is calculated as the following:

$$V_{Ripple} \approx \Delta I_L \times R_{CO\_ESR}$$

Where V_{RIPPLE} is the output voltage ripple, ΔI_L is the peak-to-peak inductor ripple current; R_{CO_ESR} is the equivalent series resistance of the output capacitor.

To get low output ripple, a low ESR value is needed. However, if the ESR is extremely low, there is a possibility of an unstable feedback loop, resulting in an oscillation at the output. So if a very low output ripple voltage is required, an optional post LC filter (see Figure 5) can be cascaded with the output.

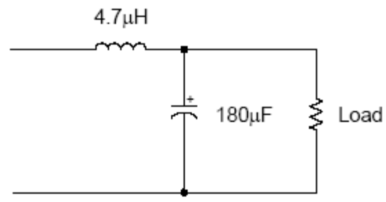

Figure 5. LC Filter

Electrolytic capacitors are not recommended for temperatures below −25°C. The ESR rises dramatically at cold temperatures and typically rises 3X at −25°C and as much as 10X at −40°C. See curve shown in Figure 6.

Solid tantalum capacitors have a much better ESR spec for cold temperatures and are recommended for temperatures below −25°C.

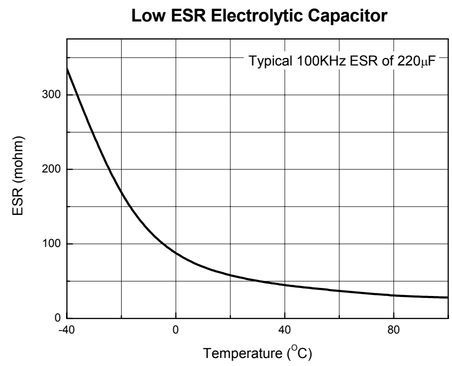

Figure 6. Electrolytic Capacitor ESR vs. Temperature

3.3 Input Capacitor - C_{IN}

The input current to the step-down converter is discontinuous, so a capacitor is required to supply the AC current to the step-down converter while maintaining the DC input voltage. A low ESR capacitor is required to keep the noise at the IC to a minimum. Ceramic capacitors are preferred, but tantalum or low ESR electrolytic capacitors will also suffice.

The input capacitor (C_{IN} in Figure 2), must be connected to the V_{IN} pin and GND pin of the AP3005 to maintain steady input voltage and filter out the pulsing input current. The voltage rating of input capacitor must be greater than maximum input voltage plus ripple voltage.

The input ripple voltage can be approximated by the equation below:

$$\Delta V_{IN} = \frac{I_{OUT}}{f \times C_{IN}} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times \frac{V_{OUT}}{V_{IN}}$$

Since the input current is discontinuous in a buck converter, the current stress on the input capacitor is another concern when selecting the capacitor. For a buck circuit, the RMS value of input capacitor current can be calculated by:

$$I_{CIN\_RMS} = I_{OUT} \times \sqrt{\frac{V_{OUT}}{V_{IN}}\left(1 - \frac{V_{OUT}}{V_{IN}}\right)}$$

If make m equal the conversion ratio:

$$\frac{V_{OUT}}{V_{IN}} = m$$

The relationship between the input capacitor RMS current and voltage conversion ratio is calculated and shown in Figure 7. It can be seen that when V_{OUT} is half of V_{IN}, C_{IN} is under the worst current stress. The worst current stress on C_{IN} is 0.5 x I_{OUT}.

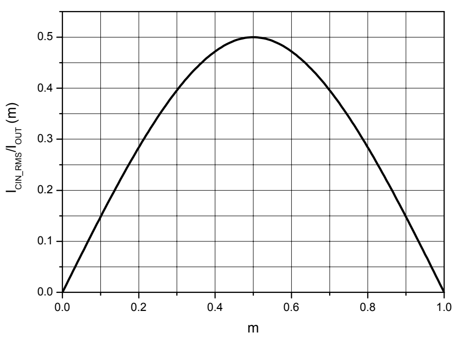

Figure 7. ICIN_RMS vs. Voltage Conversion Ratio

For reliable operation and best performance, the input capacitors must have current rating higher than I_{CIN_RMS} at the worst operating conditions. Ceramic capacitors are preferred for input capacitors because of their low ESR and high ripple current rating. Depending on the application circuits, other low ESR tantalum capacitors or aluminum electrolytic capacitors may also be used. When selecting ceramic capacitors, X5R or X7R type dielectric ceramic capacitors are preferred for their better temperature and voltage characteristics. Note that the ripple current rating from capacitor manufacturers is based on certain amount of life time. Further de-rating may be necessary for practical design requirement.

3.4 Inductor - L1

All switching regulators have two basic modes of operation; continuous and discontinuous. The difference between the two types relates to the inductor current, whether it is flowing continuously, or if it drops to zero for a period of time in the normal switching cycle. Each mode has distinctively different operating characteristics, which can affect the regulators performance and requirements. Most switcher designs will operate in the discontinuous mode when the load current is low.

The AP3005 (or any of the Simple Switcher family) can be used for both continuous (CCM) and discontinuous (DCM) modes of operation.

In many cases the preferred mode of operation is the continuous mode. It offers greater output power, lower peak switch, inductor and diode currents, and can have lower output ripple voltage. But it does require larger inductor values to keep the inductor current flowing continuously, especially at low output load currents and/or high input voltages.

The inductor is used to supply smooth current to output when it is driven by a switching voltage. The higher the inductance, the lower the peak-to-peak ripple current, as the higher inductance usually means the larger inductor size, so some trade-offs should be made when select an inductor.

Assuming that the IC is operating in the CCM and the peak-to-peak inductor ripple current is 26% of the maximum output current, an inductor value L1 can be selected as the following:

$$L1 = V_{OUT} \times \frac{V_{IN} - V_{OUT}}{f \times V_{IN} \times 26\% \times I_{OUT}}$$

Where V_{OUT} is the output voltage, V_{IN} is the input voltage, I_{OUT} is the output current.

Another important parameter for the inductor is the current rating. If inductor value has been selected, the peak inductor current can be calculated as the following:

$$I_{PEAK} = I_{OUT} + \frac{(V_{IN} - V_{OUT}) \times V_{OUT}}{2 \times V_{IN} \times f \times L1}$$

Where f is the oscillator frequency. It should be ensured that the current rating of the selected inductor is1.5 times of the I_{PEAK}.

Exceeding an inductor's maximum current rating may cause the inductor to overheat because of the copper wire losses, or the core may saturate. If the inductor begins to saturate, the inductance decreases rapidly and the inductor begins to look mainly resistive(the DC resistance of the winding). This can cause the switch current to rise very rapidly and force the switch into a cycle-by-cycle current limit, thus reducing the DC output load current. This can also result in overheating of the inductor and/or the AP3005. Different inductor types have different saturation characteristics, and this should be kept in mind when selecting an inductor.

The inductor manufacturer's data sheets include current and energy limits to avoid inductor saturation.

3.5 Catch Diode - D1

Buck regulators require a diode to provide a return path for the inductor current when the switch turns off. This must be a fast diode and must be located close to the AP3005 using short leads and short printed circuit traces.

Because of their very fast switching speed and low forward voltage drop, Schottky diodes provide the best performance, especially in low output voltage applications (5V and lower). Ultra-fast recovery, or High-Efficiency rectifiers are also a good choice, but some types with an abrupt turnoff characteristic may cause instability or EMI problems. Ultra-fast recovery diodes typically have reverse recovery times of 50 ns or less. Rectifiers such as the 1N5400 series are much too slow and should not be used.

If the power supply design must withstand a continuous output short, the diode should have a current rating equal to the maximum current limit of the AP3005. The most stressful condition for this diode is an overload or shorted output condition.

The reverse voltage rating and the current rating of the catch diode should ensure the system to function normally with a certain safety margin. The reverse voltage should be over 2 times of the system operating voltage and the current rating should be over 1.5 times of the output current.

Schottky diodes such as 1N5800 series can provide very good performance due to their fast speed and low forward voltage drop, especially in low output voltage applications.

3.6 Feedforward Capacitor – C1

When the output voltage is greater than 10V or C_{OUT} has a very low ESR, a feedforward capacitor C1, shown across R2 in Figure 2, should be added. This capacitor adds a zero point to the loop which increases the phase margin for better loop stability. The feedforward capacitor is typically between 100pF and 30nF. Typical C1 value for various output voltages can be calculated as the following:

$$C_1 = \frac{1}{31 \times 10^3 \times R2}$$

3.7 Loop Compensation

The AP3005 uses voltage-mode ('VM') PWM control to correct changes in output voltage due to line and load transients. VM requires careful small signal compensation of the control loop for achieving high bandwidth and good phase margin.

The control loop is comprised of two parts. The first is the power stage, which consists of the duty cycle modulator, output inductor, output capacitor, and load. The second part is the error amplifier, op-amp used in the classic inverting configuration. Shows the regulator and control loop components.

One popular method for selecting the compensation components is to create Bode plots of gain and phase for the power stage and error amplifier. Combined, they make the overall bandwidth and phase margin of the regulator easy to see. Software tools such as Excel, MathCAD, and MatLab are useful for showing how changes in compensation or the power stage affect system gain and phase.

The power stage modulator provides a DC gain A_{DC} that is equal to the input voltage divided by the peak-to-peak value of the PWM ramp. This A_{DC} is 1000V/V for the AP3005. The inductor and output capacitor create a double pole at frequency f_{DP}, and the capacitor ESR and capacitance create a single zero at frequency f_{CO_ESR}.

$$f_{DP} = \frac{1}{2\pi}\sqrt{\frac{R_{OUT} + R_L}{LC_{OUT}(R_{OUT} + R_{COESR})}}$$

$$f_{CO\_ESR} = \frac{1}{2\pi \times C_{OUT} \times R_{COESR}}$$

In the equation for f_{DP}, the variable R_L is the power stage resistance, and represents the inductor DCR plus the on resistance of the top power MOSFET. R_{OUT} is the output voltage divided by output current. The values of the compensation components given in Table 2 .

V_{OUT}	R_2	R_C	C_C	L_1	C_{OUT}
2.5V	43K	8.2K	10nF	22μH	22μF
3.3V	62K	8.2K	10nF	22μH	22μF
5.0V	107K	8.2K	10nF	22μH	22μF
9V	205K	7.5K	10nF	22μH	22μF
12V	280K	7.5K	10nF	22μH	22μF

Table 2. Compensation Values R-C (Ceramic) Combinations (Ceramic Output Capacitor, V_{IN}=10V to 24V)

V_{OUT}	R_2	R_C	C_C	L_1	C_{OUT}
2.5V	43K	8.2K	10nF	22μH	100μF
2.5V	43K	8.2K	10nF	22μH	220μF
2.5V	43K	8.2K	10nF	22μH	330μF
3.3V	62K	8.2K	10nF	22μH	100μF
3.3V	62K	8.2K	10nF	22μH	220μF
3.3V	62K	8.2K	10nF	22μH	330μF
5.0V	107K	8.2K	10nF	22μH	100μF
5.0V	107K	8.2K	10nF	22μH	220μF
5.0V	107K	8.2K	10nF	22μH	330μF

Table 3. Compensation Values R-C (Ceramic) Combinations (Electrolytic Output Capacitor, V_{IN}=10V to 24V)

4. PCB Layout Consideration

PCB layout is very important to the performance of AP3005 series ICs. The power path includes the input capacitors, output inductor, and output capacitors. Keep these components on the same side of the PCB and connect them with thick traces or copper planes on the same layer. Vias add resistance and inductance to the power path, and have high impedance connections to internal planes than do top or bottom layers of a PCB. If heavy switching currents must be routed through vias and/or internal planes, use multiple vias in parallel to reduce their resistance and inductance. The power components must be kept close together. The longer the paths that connect them, the more they act as antennas, radiating unwanted EMI.

The external components should be placed as close to the IC as possible. Special attention should be paid to the route of the feedback wiring. Try to route the feedback trace as far from the inductor and noisy power traces as possible. For AP3005, locate the feedback divider resistor network near the feedback pin with short leads. The feedback trace should connect the positive node of the output capacitor and connect to the top feedback resistor (R2). Using surface mount capacitors also reduces lead length and lessens the chance of noise coupling into the effective antenna created by through-hole components.