AN13532

On-chip DC-DC Converter for LPC55xx Family

Rev. 0 — 21 March 2022 Application Note

Contents

1 Introduction

All the LPC55xx sub-family processors have an internal DC-DC buck converter, which can convert high input power supply voltage ranging from 1.8 V to 3.3 V to a low power supply voltage about 1.1 V.

This application note describes the DC-DC buck converter general theory and working mechanism, gives the basic equations for the DC-DC converter, and gives the formula for the ripple of output voltage and cycle time of PFM signal. It also describes the control regulation of the DC-DC converter, gives the basic specs of the DC-DC buck converter, discusses the consideration of selecting the inductor and bypass capacitor.

2 Power supply conversion

It is widely used to convert a DC voltage to another level DC voltage, currently, there are two mechanisms to convert the DC voltage to another DC voltage, one is linear regulator mechanism, another is switch mode power supply mechanism. The linear regulator has the features, such as higher output voltage stability, easy design, but the disadvantage is low power conversion efficiency. The bigger the voltage difference between input voltage and output voltage is, the lower efficiency of the linear regulator is, furthermore the temperature of regulator will be high when the load is heavy because of low efficiency. The linear regulator is preferred for the analog device power supply because of the linear regulator output voltage stability feature (low ripple voltage). Note that the linear regulator can only convert from high input voltage to low output voltage, the LDO (Low-Dropout Regulator) is a specific linear regulator which can have lower drop voltage between input voltage and output voltage.

The DC-DC converter uses switch mode power supply mechanism to convert DC voltage to another level DC voltage, which has high power conversion efficiency, but the disadvantage is the output voltage is not stable. In other words, the output voltage has ripple, moreover the design is difficult. Therefore, the DC-DC converter can provides power for the digital circuit, because digital circuit is not sensible for the power supply voltage ripple, partly because the DC-DC converter has higher efficiency.

2.1 Linear regulation introduction

This is a typical linear regulator application which is copied from a DSC schematic, which converts 5 V power supply to 3.3 V power supply, on both the input side and the output side, a large bypass capacitor is required. The value of the bypass capacitor is proportional to the current. Generally, for 1 A DC current, the required capacitor is about 10 μF.

In order to compute the efficiency, assume that the load on 3.3 V power supply is 1 A current. Based on the circuit theory, the input current equals to output current. As 5 V power supply input current is 1 A, so the input power is 5 V*1 A=5 W and the output power is 3.3 V*1 A=3.3 W. Therefore, the power efficiency is 3.3 W/5 W*100%=66%. The remaining power 1.7 W generates heat on the regulator device, which leads to temperature rise for the regulator device.

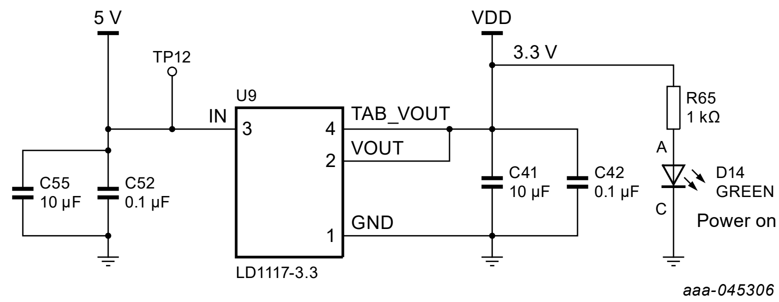

Figure 1. Linear regulator

2.2 DC-DC converter introduction

The DC-DC converter is based on switch mode power supply technology to convert DC input voltage to desired output voltage. It charges a capacitor with chopping the DC input voltage via power device and then smooth the voltage to get the desired output voltage.

From the types of DC-DC converter, there are two types of DC-DC converter, one type is DC-DC converter with galvanic isolation transformer especially in high voltage application, another type is DC-DC converter without transformer especially in low voltage application.

The DC-DC converter with transformer is widely used in application which gets energy from AC line power. The AC line power is rectified and becomes DC voltage with 4 diodes and capacitor filter, then a DC transformer is used to change the voltage ratio between output DC voltage and input DC voltage based on ratio of coil number between primary and secondary windings, secondly to isolate the secondary from primary winding galvanically, the isolation can protect the human being from the AC line power.

For example, each notebook computer has a AC-DC adapter, which converts AC to high voltage DC with rectifier circuit, then uses a DC-DC converter with galvanic isolation transformer to get about 19 V DC output voltage.

The DC-DC converter without transformer is widely used in low voltage application. The DC-DC converter from low voltage to high voltage is called boost converter. The DC-DC converter from high voltage to low voltage is called buck converter. As there is no transformer, the input voltage and output voltage share the same ground, so no isolation is implemented.

2.2.1 Mechanism of DC-DC circuit for buck converter

The working sequence of buck converter consists of three stages: stage1, stage2, and stage3. During stage 1, input power supply charges the capacitor via inductor L. During stage 2, residual energy saved in inductor L charges the capacitor. During stage 3, the capacitor discharges current to load, in other words, the load get energy from capacitor.

2.2.2 Stage1 with P MOSFET on and diode off

In Figure 2, assume that a high voltage DC power supply is impressed on the V_{in} and GND terminal, and a low voltage on the V_{out} and GND terminal is expected.

When the P MOSFET is turned on by controller, current will flow from V_{in} input terminal, flow through P MOSFET, through the inductor L, then charge the capacitor C. The current flows as shown in the blue line. During the process, energy is transferred from V_{in} port to capacitor C and finally output voltage at V_{out} terminal is established.

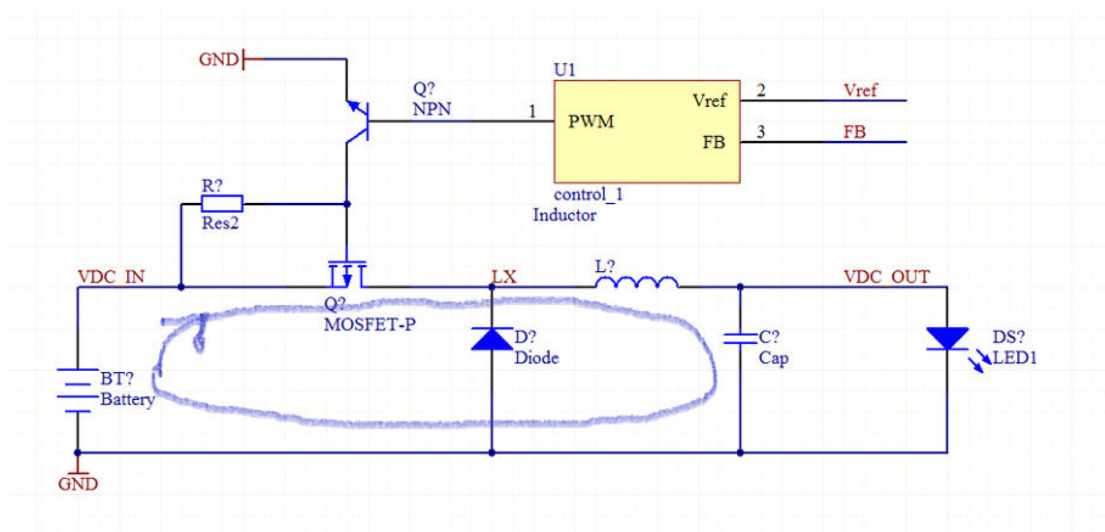

Figure 2. Buck circuit with MOSFET on and diode off

NOTE

The P MOSFET is selected because it is easy to use a pre-driver to control the Gate pin of MOSFET.

Here, a LED is drawn which represents any load, and can consume energy.

V_{in} is the high-voltage DC power supply input terminal (the same node as VDC_IN in Figure 2) and V_{out} is the low-voltage DC power supply output terminal (the same node as VDC_OUT in Figure 2).

2.2.3 Stage2 with MOSFET off and diode on

When the P MOSFET turns off by controller, because of the inductor L current decrease, the node has negative voltage which the inductor, P MOSFET D port and diode N port are connected with, so the diode will turn on, the current flows from GND to inductor via diode, then charge the capacitor C. The current flows as the blue line, the turning-on of the freewheeling diode is a transient process, the diode turns-on automatically without any control because of inductor freewheeling feature, and turns-off automatically when the current flowing through the diode attenuates to zero. During the process, energy is transferred from L inductor to capacitor.

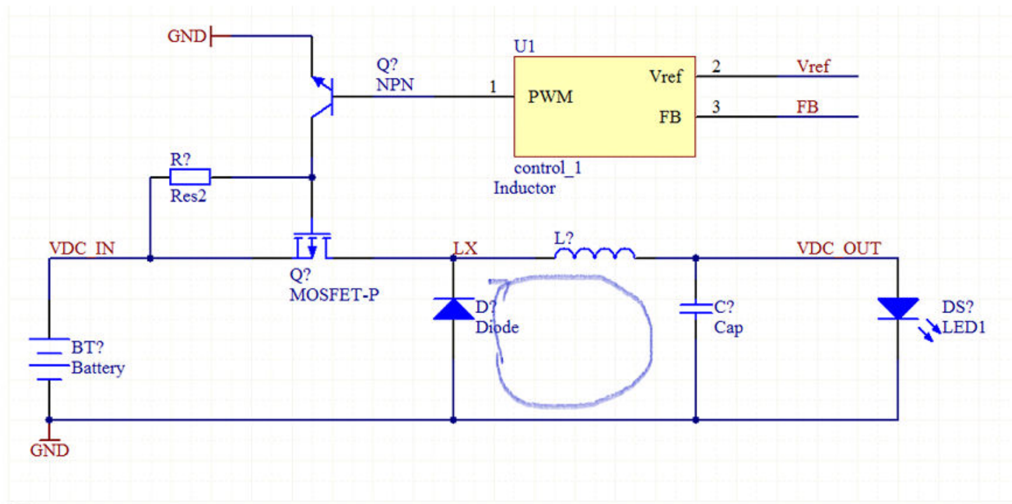

Figure 3. Buck circuit with MOSFET off and diode on

2.2.4 Stage3 with MOSFET off and diode off

After the diode turning-on transient process is over, both the P MOSFET and diode turn off, the charged capacitor provides power for the load. Here the LED represents the load. The current flows as the blue line.

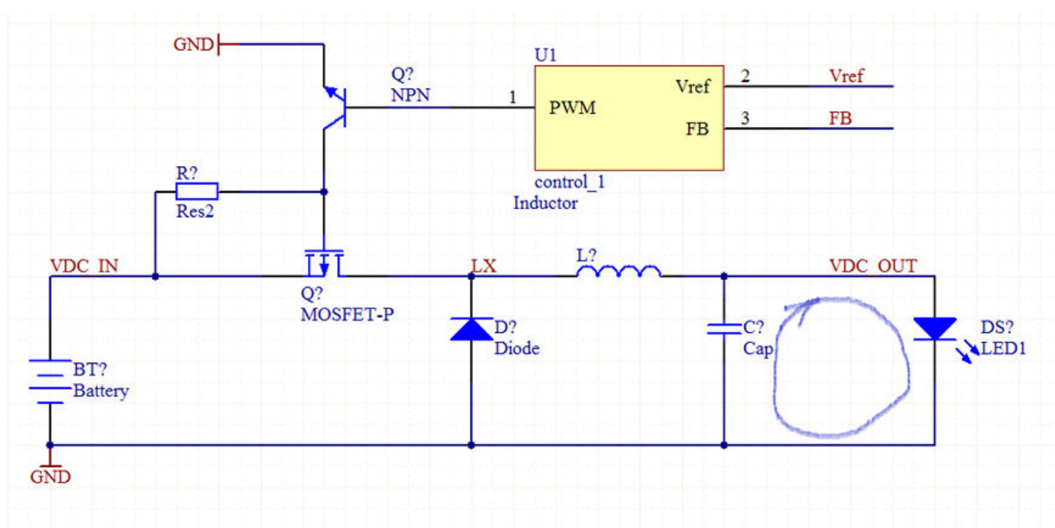

Figure 4. Buck circuit with both MOSFET and diode off

3 Buck circuit analysis

3.1 Incremental current when the P MOSFET is on

Based on Figure 2, When the MOSFET is on, the current flowing through L will increase from 0 to ΔI based on Equation 1:

$$U=L*di/dt$$

Equation 1.

Here, L is the inductance of inductor, U is the voltage impressed on the two ends of inductor L, i is the current flowing through the L, t is the time.

- When the MOSFET is on, the incremental current during the interval of MOSFET turning-on time is:

$$\Delta I=\frac{1}{L}\int(Vin-Vout)dt = (Vin-Vout)*T\_mosfet\_on/L$$

Equation 2.

Where:

- T_mosfet_on is the time during which the MOSFET turns on.
- V_{in} is the input power supply voltage
- V_{out} is the output power supply voltage
- L is the inductance value of inductor
- **ΔI** is the incremental current flowing through the inductor L at the instant when the MOSFET completes turning-on and becomes off.

3.2 Time when the freewheeling diode is on

When the diode is on, the current flowing through L will attenuate naturally from **ΔI** to zero.

After the MOSFET is turned off by the controller, the Diode will turn on naturally because of inductor freewheeling feature, when the diode is on, the node where the inductor, P MOSFET D pin and diode N port are connected has negative voltage. The voltage on the two ends of inductor L is GND and V_{out}. Based on Equation 1, the diode turning-on time T_{Diode_on} can be figured out as:

$$T_{Diode\_on}=\frac{L*\Delta I}{Vout}$$

Equation 3.

Where:

- ΔI is the current flowing through the inductor L when the MOSFET switches from on to off state
- V_{out} is the output power supply voltage
- T_{Diode_on} is the time during which the diode is on, in other words, it is the time that the inductor current attenuates from ΔI to zero

3.3 Ripple voltage on the V_{out} port

The sum of charges on the capacitor when the MOSFET is turned on and diode is on.

$$\Delta Q=\int i\,dt=\frac{1}{2}\Delta I*(T_{mosfet_{on}}+TDiode\_on)$$

Equation 4.

The voltage ripple on the capacitor is ΔQ/C when the current component discharging to load is neglected for simplicity during both P MOSFET turning-on time and diode turning-on time.

$$Vout_{ripple}=\Delta Q/C=\Delta I*(T\_mosfet\_on + T_{Diode\_on})/(2*C)$$

Equation 5.

Where:

- C is the capacitance value of capacitor
- T_mosfet_on is the time during which the MOSFET turns on.
- TDiode_on is the time during which the diode is on
- ΔI is the current flowing through the inductor L when the MOSFET switches from on to off state.

Substituting ΔI and T_{Diode_on} with Equation 2 and Equation 3, we get:

$$Vout_{ripple}=\frac{T\_MOSFET\_on^2*(Vin-Vout)*Vin}{2C*L*Vout}$$

Equation 6.

From the above Equation 6, after the charging process completes, the incremental voltage of capacitor(ripple voltage) can be estimated, it is dependent on the MOSFET turn-on time, the inductance value of inductor and the capacitance value of capacitor.

For the LPC55xx DC-DC converter, fixed MOSFET turn-on time control regulation is adopted. So it is required that user must follow up the value of external inductor and capacitor, otherwise, the ripple will be out of range.

3.4 Cycle time of the PFM signal

The T_{idle} is the time from diode turning off to the instant that the next P MOSFET is on, during the T_{idle}, both the MOSFET and Diode are off, the capacitor C discharges to the load, so the V_{out} voltage will decrease.

In steady state and in one cycle, the charges charged on capacitor by V_{in} power supply equals to the charges discharged from the capacitor to the load, with the capacitor charge balance, we can get:

$$\frac{1}{2}\Delta I*(T\_mosfet\_on + T_{Diode\_on})=I_0*(T\_mosfet\_on + T_{Diode\_on} + T_{idle})= I_0*T_{cycle}$$

Equation 7.

Here,

- **ΔI** is the current flowing through the inductor L when the MOSFET switches from on to off state.
- I0 is the assumed load current in one cycle.
- T_{idle} is the time during which both MOSFET and Diode are off, the capacitor provides power for the load.
- T_{cycle} is the cycle time, which consists of $T\_mosfet\_on + T_{Diode\_on} + T_{idle.}$

Substituting the ΔI with Equation 2, the T_{Diode_on} with Equation 3, we can get:

$$T_{cycle}=\frac{(Vin-Vout)*Vin}{2*L*I0*Vout} * T_{MOSFET\_on}^2$$

Equation 8.

From Equation 8, for the LPC55xx DC-DC converter, all the Vin, Vout, L are fixed, the T_{MOSFET_on} is also fixed because the PFM is selected as control regulation.

We can see that the T_{cycle} is inverse proportional to the load current $I_{0,}$ this is institutive that the higher the load current is, the shorter the PFM cycle is.

4 DC-DC operating mechanism and control regulation

4.1 PWM signal vs PFM signal

Here, the so-called control scheme is the regulation to adjust the MOSFET on-time or off-time in real time so that the DC-DC converter output voltage approaches to a pre-specified reference voltage with variable load even variable input voltage, and furthermore the transient time is required to be short enough. The DC-DC converter uses PWM or PFM or the other waveform signal to control the MOSFET on or off to control the DC-DC output voltage, the PWM or PFM signals is the essence of the control system.

The PWM means Pulse Width Modulation, the duty cycle of PWM signal can be variable cycle by cycle, but the PWM cycle time is fixed.

The PFM means Pulse Frequency Modulation, it has two types, the fixed on-time type and the fixed off-time type. For the fixed on-time type, the off-time varies with time, so the PFM signal cycle time varies cycle by cycle. For the fixed off-time PFM signal, the on-time varies cycle by cycle. So irrespective of fixed on-time or fixed off-time, the PFM cycle time varies cycle by cycle. The advantage of the PFM signal is its spread frequency spectrum, variable frequency can reduce EMI emission when the control signal drives power device.

The DC-DC converter of LPC55xx is only an accessory module of LPC55xx, the DC-DC control system must be simple, so the PFM control regulation is selected with fixed on-time. Because the cycle time of PFM signal is sum of on-time and off-time, so the cycle time varies with load, the cycle time is NOT constant.

The following signal waveform is PFM signal with fixed on-time and variable off-time.

In this application note, the PWM and PFM names are interchangeable, because the functions are same. The only difference is the waveform, the on-time is variable for PWM, the on-time is fixed for PFM.

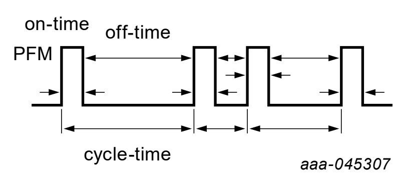

Figure 5. PFM signal waveform with fixed on-time

4.2 MOSFET driving signal

For the DC-DC converter of LPC55xx, the MOSFET, diode and corresponding controller are integrated internally, but the inductor and capacitor components have to be connected externally because of large size, so in Figure 6, all components inside the blue circle are integrated into the LPC55xx, all components outside the circle are connected externally. The “LX” is the external pad of LPC55xx internal DC-DC converter, where internal P MOSFET and diode are connected together. The LX pad requires to be connected to external 4.7 µH inductor and 22 µF capacitor. The working procedure is as the above procedures. The DC-DC converter load is the VDD_MPU pin, which provides power for the core of LPC55xx and the digital peripheral in active mode.

For the P MOSFET driving circuit, when the P MOSFET Gate voltage Vgs is a negative voltage, the P MOSFET will turn on, when the Gate voltage Vgs is a zero, the P MOSFET will turn off.

So if the MOSFET is required to be connected serially in a circuit, the P MOSFET is preferred because pre-driver circuit is simple, that is why the P MOSFET is selected in the buck circuit for LPC55xx. In detail, a transistor is used as a pre-driver to drive P MOSFET as shown in Figure 6, when the PWM signal is high, the NPN transistor turns on, the gate voltage of P MOSFET is LOW, the Vgs(the voltage between gate and source) voltage of P MOSFET is negative, the P MOSFET turns on, the power supply with

VDC_IN terminal will charges the capacitor through inductor. When the PWM signal is LOW, the NPN transistor will turn off, the Vgs will be zero and the P MOSFET will turn off.

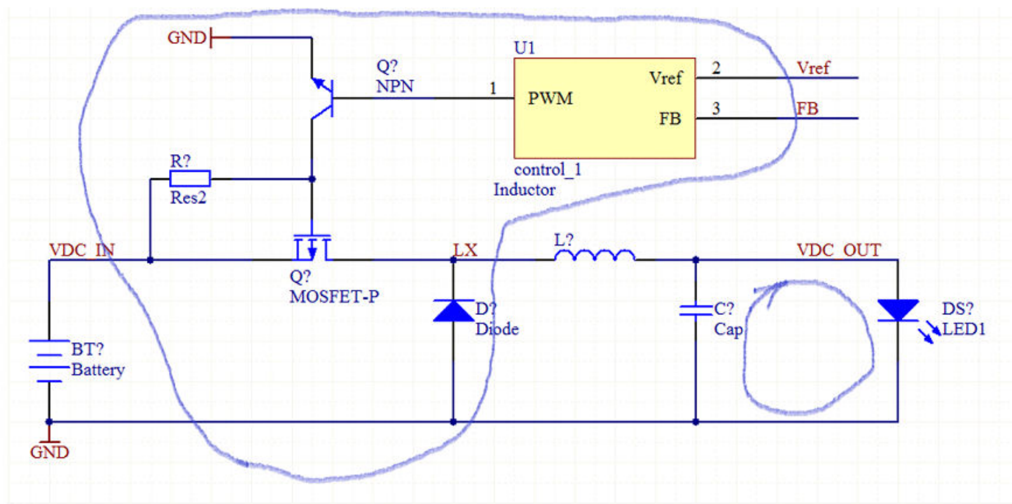

Figure 6. Buck circuit diagram

4.3 DC-DC converter working sequence and signal waveform explanation

In Figure 7, the X coordinator is time and the Y coordinator is the voltage or current signals. The V_be is the PWM signal waveform(PFM) which drives the base of transistor. As shown in Figure 6, the V_LX signal is the signal voltage waveform on the LX pad of LPC55xx, the I_LX is the current value on the LX pad with the time, the I_LX0 is the average value of the I_LX, because the I_LX is a current waveform with time, it cannot be observed with oscilloscope directly, the VDC_OUT is the voltage on the capacitor, also the DC-DC converter output voltage, the VDC_OUT0 is the average voltage of the capacitor based on Figure 6.

In Figure 7, the cycle of buck converter consists of three stages: stage1, stage2 and stage3, which corresponds to the three stages discussed in Mechanism of DC-DC circuit for buck converter.

Stage 1: During stage 1, the buck circuit charges the capacitor. The PFM signal is high logic, the transistor turns on, the P MOSFET turns on, external power supply charges the capacitor, current curve flowing through the inductor is the I_LX curve, the incremental current ΔI is as shown in equation 2.

Because there is current to charge the capacitor, the voltage of the capacitor increases. The capacitor voltage curve vs time is the VDC_OUT curve. VDC_OUT0 is the average voltage in one cycle.

Stage 2: During stage 2, the buck circuit charges the capacitor. Because the PFM signal is the LOW logic, the transistor turns off and the P MOSFET turns off. Because of the inductor freewheeling feature, the inductor tries to keep the original current. The LX pad becomes a negative voltage. The diode turns on. The current flows from GND to charge the capacitor via the diode and inductor. The energy stored in the inductor transfers to the capacitor. The current curve flowing through the inductor attenuates from ΔI to 0 as the I_LX curve during stage 2, the current curve vs time follows up equation 3.

Because there is current to charge the capacitor, the voltage of capacitor will increase, but the increasing rate of the VDC_OUT is reduced compared to stage 1.

Stage 3: During stage 3, the buck circuit does not charge the capacitor while discharge to load, the PFM signal is LOW logic, the transistor turns off, the P MOSFET turns off, the diode freewheeling process is completed so the diode turns off, the capacitor is not charged. The V_LX is the LX pad voltage, which is the same as capacitor voltage during stage 3 because the current flows through the inductor is zero during stage 3. The I_LX is zero in stage 3. Because the load consumes current, the capacitor voltage reduces, assuming that the load consuming current is constant, the capacitor voltage reduces linearly with time so the VDC_OUT voltage is shown in stage 3 in Figure 7.

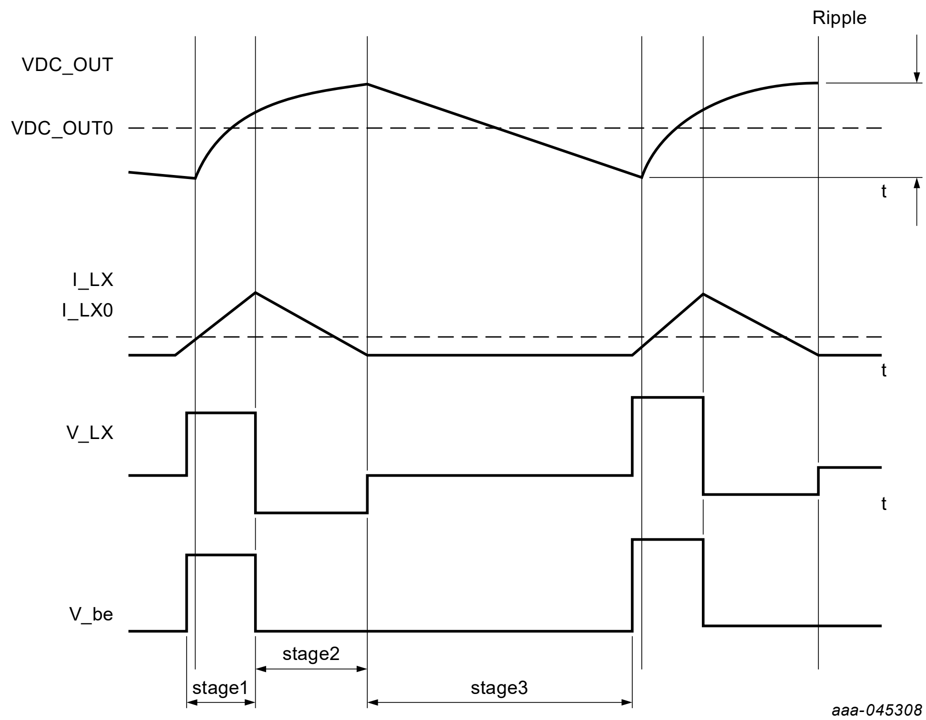

Figure 7. Signal waveform of the buck circuit

NOTE

The VDC_OUT ripple voltage is exaggerated in order to elaborate the DC-DC output voltage change, in reality, the ripple is only 20 mV for LPC55xx DC-DC converter.

4.4 Control scheme

The DC-DC converter of LPC55xx is an accessary module of LPC55xx, so its control regulation has to be simple. Based on Figure 6, the yellow block is the controller, the controller has three signals: FB, Vref, and PWM signal, the FB and Vref signal are input signal, the PWM signal is output signal for the controller.

The FB signal is the external pad of LPC55xx, it is an input signal, and used to sense the DC-DC converter output voltage as feedback signal because the feedback control is used. Because the FB is an input signal pin, it does not transfer energy, so on PCB, it can be treated as a signal with normal signal width trace when PCB is designed.

The Vref pin is an internal pin without external pad, which is used to set up the DC-DC converter reference voltage by internal DAC or whatever, for example, if you want 1.1 V DC-DC output voltage, set the Vref as 1.1 V, so it is an input signal for the controller. The PWM signal(PFM signal) is an output signal for the controller, used to control the gate of P MOSFET via MOSFET pre-driver.

The controller uses feedback control, the controller compares the voltage of FB signal with Vref pin voltage, which is set up by DAC or whatever, if the difference is greater than a pre-defined voltage threshold, one new cycle PFM signal is generated from the PWM pin, the PFM signal drives the P MOSFET via pre-driver, the High logic of the PFM signal can turn on the P MOSFET, the capacitor is charged by power supply from Vin terminal via inductor during stage 1 and 2. Therefore, the DC-DC converter output voltage will increase, the positive incremental voltage(ripple of the DC-DC converter output voltage) is deterministic based on equation 5. If the difference is less than a pre-defined voltage threshold, the PFM signal keeps to low logic, this is stage 3 as above mentioned.

Figure 8 is real signal waveform, the pink signal is tested at LX pin of LPC55S69 on LPCXpresso55S69 EVK board with oscilloscope, during high logic of the pink signal, the internal MOSFET is on with the PFM signal driven high by the controller and diode is off, the capacitor is charged (this is stage 1). During the Low logic of the pink signal, the MOSFET is off with the PFM signal driven Low by the controller, the internal diode turns on automatically because of inductor freewheeling feature (this is stage 2). During the time with pink signal bouncing and attenuating, both MOSFET and diode are off, because of diode reverse recovery feature from diode on to off, the LX pin voltage is shown in Figure 8 (this is stage 3).

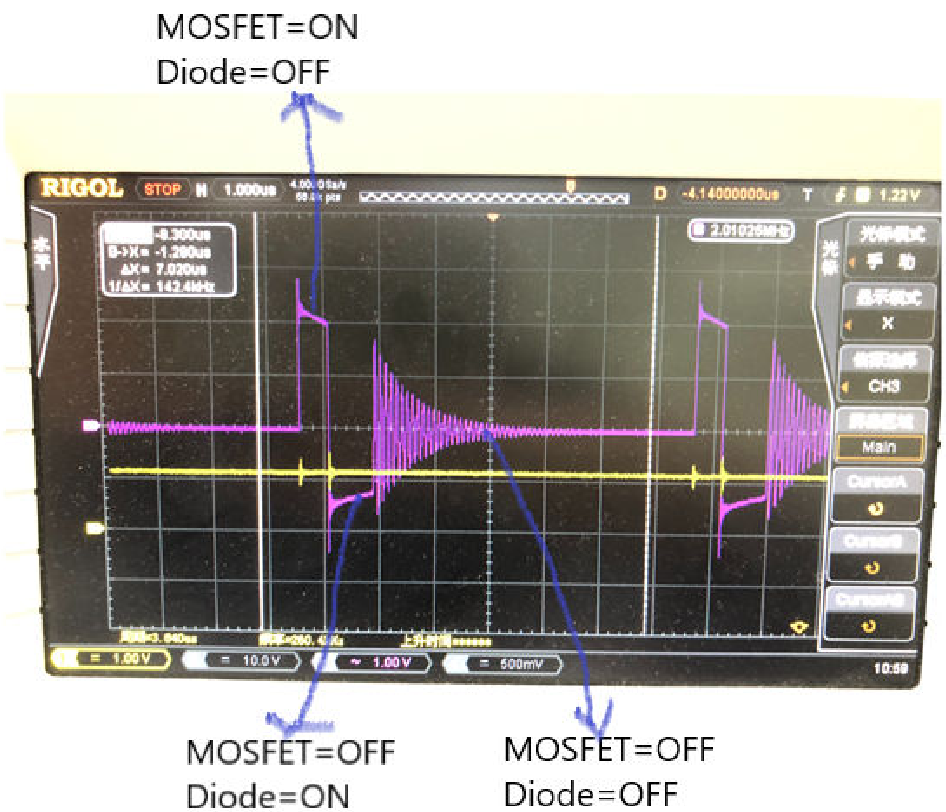

Figure 8. Waveform of LX pin with oscilloscope scope

5 DC-DC converter specs

This is the spec of LPC5569 DC-DC converter.

V_{out} pin output voltage:

The Vout pin output voltage is 1.1 V typically, the voltage can be adjusted with core frequency with the function `void POWER_SetVoltageForFreq(uint32_t system_freq_hz);` the programmable range is from 0.95 V to 1.2 V with 25 mV step.

The maximum current on the V_{out} port: 50 mA

Max of ripple voltage on V_{out} pin: 20 mV

DC-DC converter frequency range:15 KHz to 500 kHz

VBAT_DCDC input range: 1.8 V to 3.6 V

DC-DC converter efficiency: about 85%

The start-up time of the DC-DC converter: about 100 µS

6 LPC55XX power supply diagram

Figure 9 is power supply pin description, the VBAT_DCDC, VBAT_PMU, VDD, VDDA, Vref and VDD_PMU are input power supply pins, the operating voltage of VBAT_DCDC, VBAT_PMU, VDD, VDDA ranges from 1.8 V to 3.3 V, the VDD_PMU is 1.1 V. The internal DC-DC converter generates 1.1 V power supply to provide power for the VDD_PMU pin with L1 inductor and C1 capacitor components, so on the PCB, user should connect FB pin to VDD_PMU pin. From PCB design, the L1 and C1 should be as close as possible to the LX, and VDD_PMU pins. The FB pin is just used to sense DC-DC converter output voltage, it does not provide power.

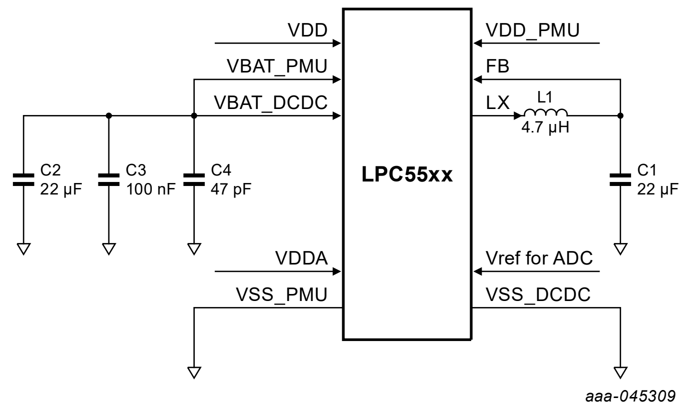

Figure 9. Power supply pins of LPC55xx

7 Capacitor and inductor selection

The capacitor C1 is charged with inductor current and discharged to load with high frequency, so the capacitor must have low Equivalent Serial Resistance (ESR) and higher frequency width. High ESR can reduce the charging/discharging current of the capacitor, at the same time, make the capacitor hot, so it is an important parameter for the capacitor, the low ESR capacitor should be selected. Compared electrolytic capacitor, tantalum capacitor and ceramic capacitor, from the high frequency response and low ESR perspective, the X7R ceramic capacitor is preferred, the X7R provides intermediate capacitance values which vary ± 15% over the temperature range of -55°C to 125°C.

For the inductor selection, the inductor is a non-standard component, its equivalent resistor should be small and its flux cannot saturate with the rated current.

The following are the inductor specs copied from AN12325.

Table 1. Power inductor

Parameter	Min	Type	Max	Unit
Inductance value	3.7	4.7	5.6	µH
Saturation current	350	500	-	mA

8 Internal power diagram of LPC55xx

In Figure 10, we can see that the VBAT_PMU pin provides power for the FRO, RTC, BOD, always-on LDO, Band GAP, if a customer just wants to operate RTC while the core and the other peripherals are off, it is OK to just connect the battery to the VBAT_PMU pin.

The VBAT_DCDC pin provides power for the DC-DC converter, and the DC-DC converter provides power for VDD_PMU pin, consequently provides power for the core of LPC55xx and the digital peripherals.

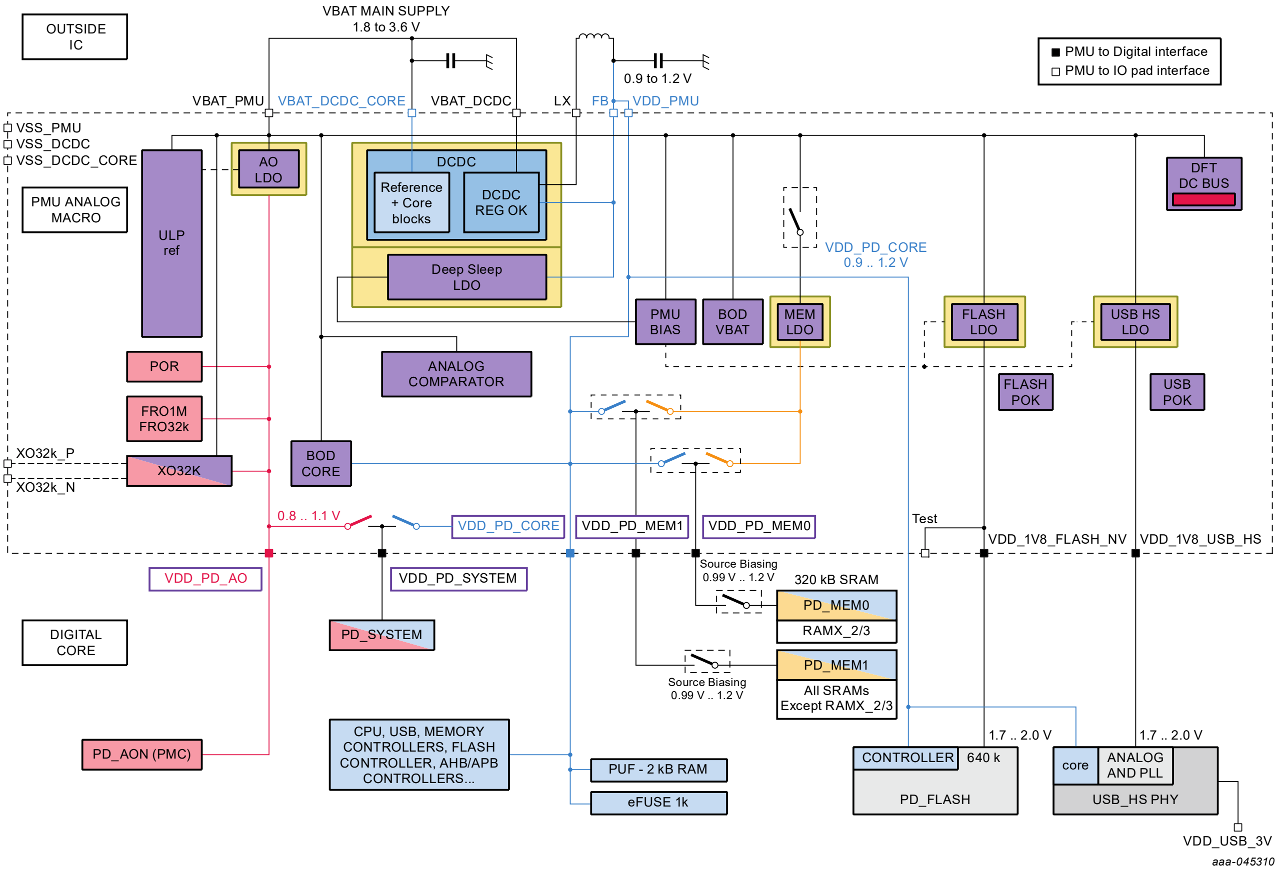

Figure 10. LPC55xx power supplies

9 Conclusion

This application note introduces the linear regulator and the DC-DC converter, describes the operating mechanism of DC-DC BUCK converter without isolation, gives the basic equation to compute the charging current, voltage ripple, and cycle time of PFM. It describes the P MOSFET pre-driving circuit and feedback control scheme, lists the specifications of the DC-DC converter, and introduces the standard to select the capacitor and inductor.

10 References

These references are available on nxp.com.

- Using the DC-DC feature (document AN12325)
- LPC55S6x/LPC55S2x/LPC552x User manual (document UM11126)
- LPC55S6x Data Sheet (document LPC55S6x)

11 Revision history

The following table lists the substantive changes done to this document since the initial release.

Table 2. Revision history

Revision number	Date	Substantive changes
0	21 March 2022	Initial release

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