

IC Laboratory

Indispensable technology for wireless mice and other ultra-low current applications

Prolonged operation with a single AA battery!

Research on PFM power supply control

The main DC-DC converter control methods are PWM (Pulse Width Modulation), which is often used as a power supply for advanced electronic equipment such as wireless devices, TVs and digital recorders, and PFM (Pulse Frequency Modulation), which is often used in step-up power supplies for wireless mice, remote controls, and other battery-driven devices where optimising battery life is most important criteria.

These methods represent the most fundamental aspect of DC-DC converter operation and are the first things a designer needs to know in order to design a high-efficiency power supply circuits.

In this article we will discuss how the use of PFM control can be beneficial for DC/DC converter in applications which only need low output currents (for example 10mA or less), but first let us outline the differences between PWM and PFM control:

● PWM control:

PWM control performs switching operation at a constant frequency, and changes the ON-time (duty-cycle) in response to the load current. In general this control method has a low output voltage ripple and offers high efficiency for larger output currents.

In addition because PWM operation uses a constant switching frequency, it is easy for the designer to implement a simple RC filter externally to reduce output noise as required. However designer should be aware that the overall efficiency of the circuit will decrease at light loads because the fixed frequency will result in un-necessary switching operations and therefore increased switching losses.

● PFM control:

A DC/DC operating in PFM mode will only make a switching operation when needed in response to the load current demand. So the number of switching operations is varied in response to the load current and thus the switching frequency can be much lower under light load conditions and un-necessary switching operations are avoided.

This lower switching frequency ensures higher efficiencies at light loads because switching losses are reduced and the overall quiescent current of the DC/DC circuit can be lower.

However compared to PWM, the PFM control method generally uses more energy per switching operation and localised continuous mode operation can easily occur which can result in a larger output voltage ripple. The designer cannot easily implement a RC filter with PFM control because the switching frequency is not fixed.

Let us now consider how these two difference control methods affect the operation waveform using the circuit shown in Fig. 1 below.

When a “high” voltage level is input into the CE pin of the XC9105 series step-up DC-DC converters PWM operation takes place. When an intermediate voltage level is input, automatic switching between PWM and PFM operation takes place in response to the load.

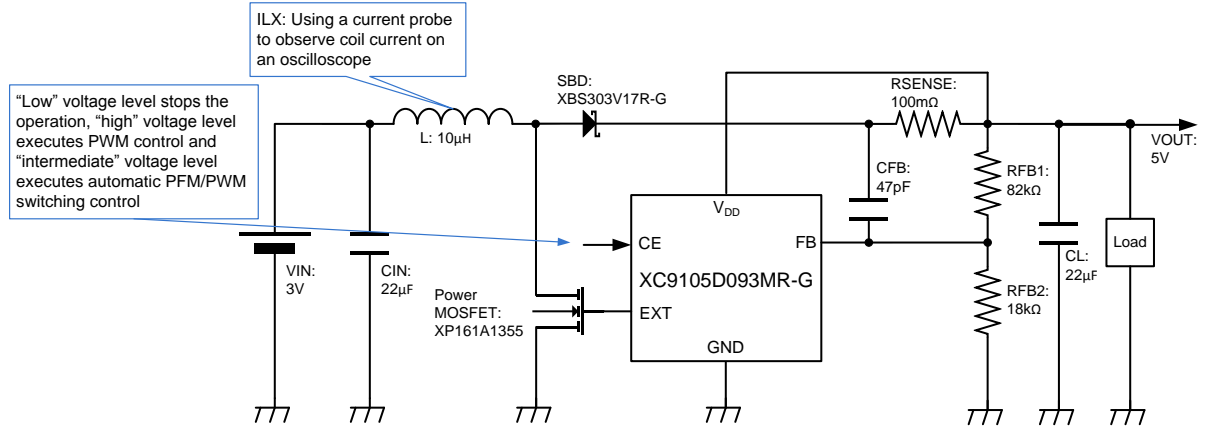
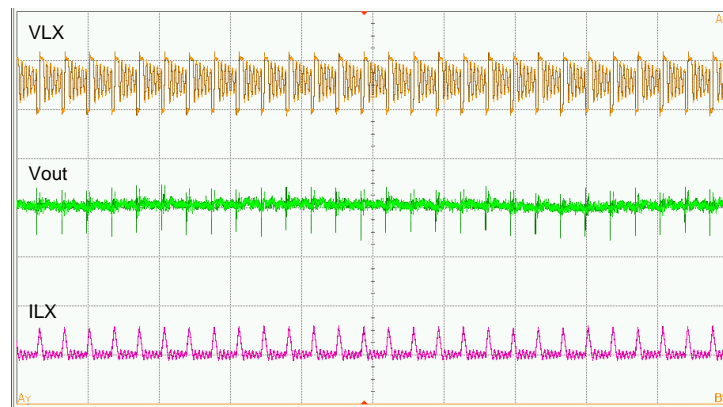
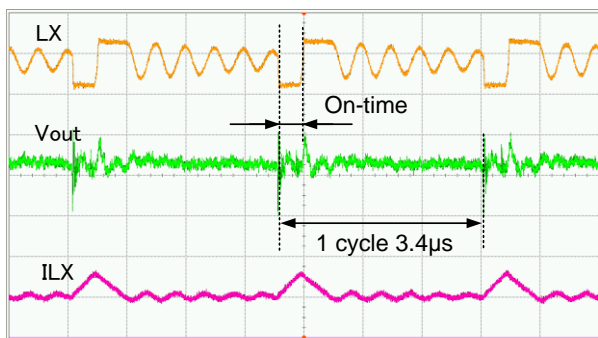


Fig. 1: Step-up DC-DC converter that allows both PWM control and PFM control waveforms to be viewed

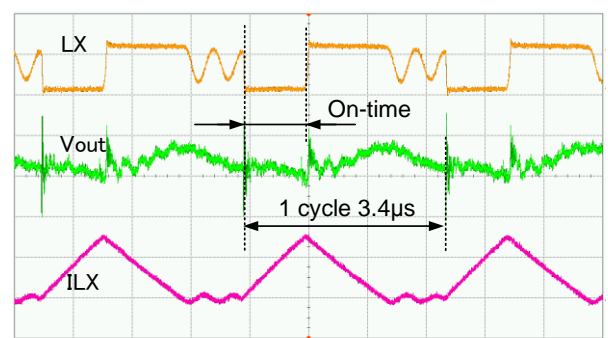
Fig. 2 shows the waveform during operation in PWM control. It can be seen that the switching frequency is held constant even when the output current changes.



(a) When output current is 5mA (10μs/div)



(b) When output current is 5mA



(c) When output current is 50mA

Fig. 2: PWM control waveforms for two different output current values (V_{LX} : 5V/div, V_{out} : 20mV/div, I_{LX} : 200mA/div, horizontal axis 1μs/div)

When the duty-cycle changes while the switching cycle is held constant, the average current in the coil increases. (non-continuous mode)

Fig. 3 shows the operation of PFM control. It can be seen that the switching frequency increases when the load current increases. Fig. 2 (a) above and Fig. 3 (a) below show the waveforms of PWM and PFM

when the time axis are the same. When operated under the same conditions, the differences between the switching frequencies of PWM operation and PFM operation and the differences in ripple voltage can be easily seen.

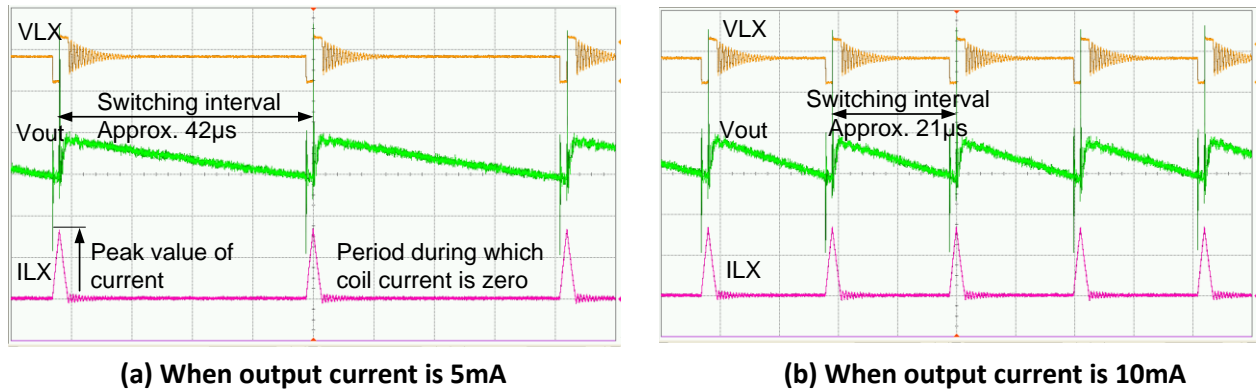


Fig. 3: Fixed ON-time PFM control waveforms for two different output current values (V_{LX} : 5V/div, V_{out} : 20mV/div, I_{LX} : 200mA/div, horizontal axis 10µs/div)

When the switching cycle shortens in Fig. 3 the output current is increased.

• Differences between fixed ON-time PFM control and current limiting PFM control

There are several types of PFM control and below we will discuss two of the most common types:

- Fixed ON-time PFM control
- Current limiting PFM control

The XC9105 in shown in Fig.1 above uses the fixed ON-time PFM control method.

By contrast, a control method that monitors coil current and turns it OFF when a set current is reached is called current limiting PFM control. The control circuit of fixed ON-time PFM control can be a relatively simple configuration such as a comparator and a timer, and thus the control IC is often an inexpensive product. The ON-time is determined, so the energy stored in the coil can be easily calculated and it is relatively easy to determine circuit constants. At the same time, the IC occasionally oscillates during operation in continuous mode, and thus is suited to non-continuous mode.

Current limiting control limits the peak current flowing through the coil and holds it constant, so a large ripple voltage does not tend to occur even at a large output current. The peak current of the coil is determined, enabling easier design of coil current ratings; however, this control method is not suitable when a large current is needed. An example of a power supply that uses a current limiting PFM control IC is shown in Fig. 4.

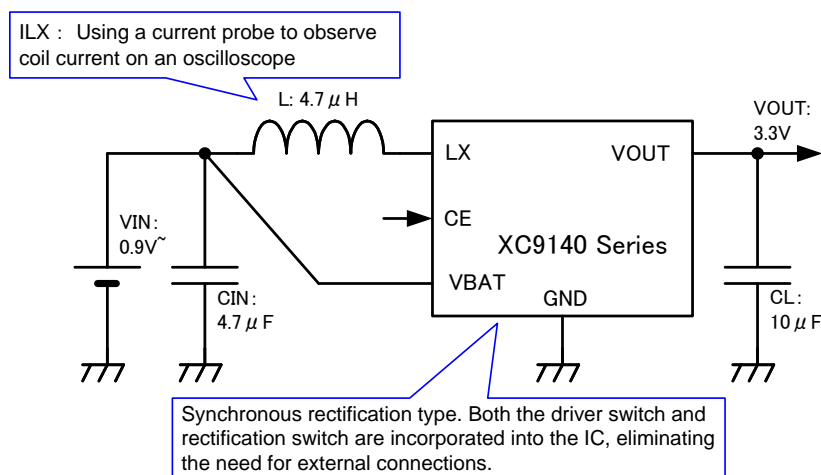


Fig. 4: Current limiting PFM control Step-up DC-DC converter

When the current flowing through the internal switch exceeds a set value, the ON state is stopped. The maximum current that flows through the coil is determined, allowing easier component selection. The waveform that is produced by fixed ON-time PFM control is shown in Fig. 5, and the waveform that is produced by current limiting PFM control is shown in Fig. 6.

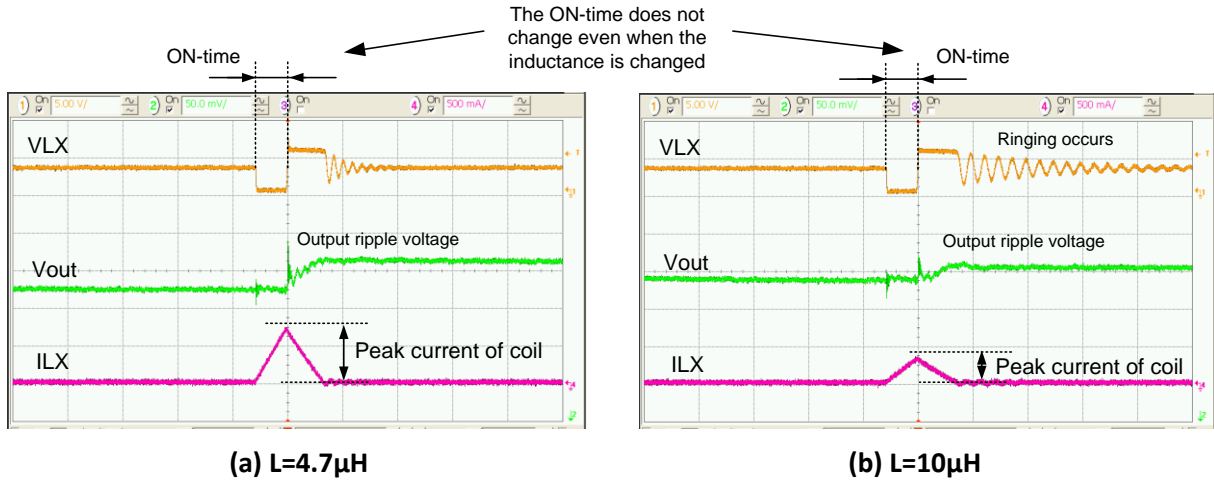


Fig. 5: Fixed ON-time PFM control waveforms for two different inductance values (V_{LX} : 5V/div, V_{out} : 50mV/div, I_{LX} : 200mA/div, horizontal axis $2\mu\text{s}/\text{div}$)

The circuit used to measure the above waveforms is that shown in Fig. 1. When the inductance is large, the current rise is gentler, and thus for the same ON-time, the peak value of the current is smaller and less energy is stored in the coil.

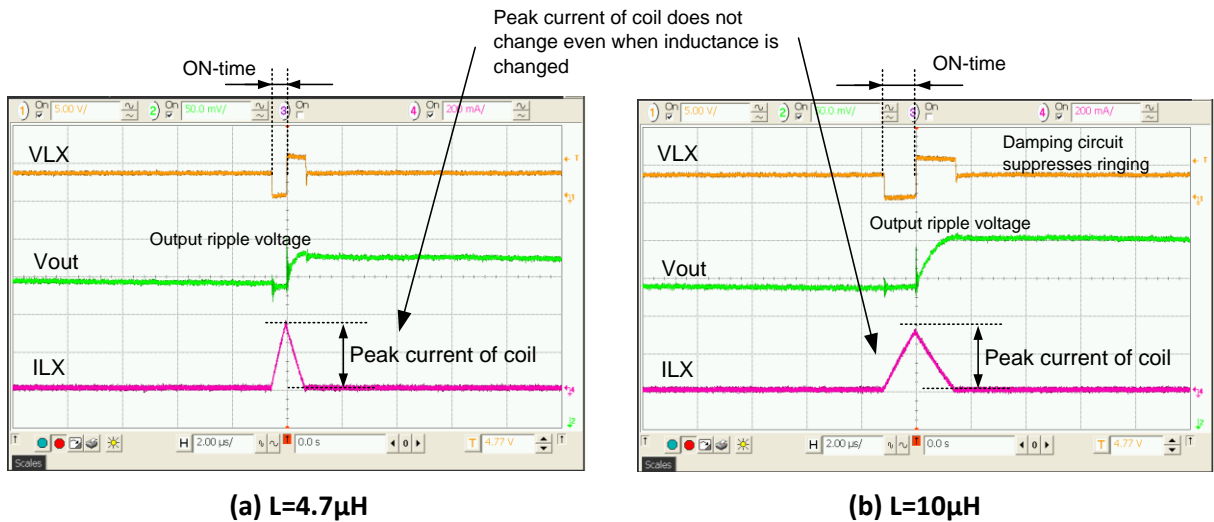


Fig. 6: Current limiting PFM control waveforms for two different inductance values (V_{LX} : 5V/div, V_{out} : 50mV/div, I_{LX} : 200mA/div, horizontal axis $2\mu\text{s}/\text{div}$)

When the peak current is constant, more energy is stored in the coil when the inductance is larger. The circuit used to measure the above waveforms is that shown in Fig. 4. The value of C_L is smaller than in Fig. 1, $10\mu\text{F}$ compared to $22\mu\text{F}$, and thus the ripple in Fig. 6 is larger than in Fig. 5.

When the inductance is increased, the ripple voltage of the output voltage decreases in fixed ON-time control, and increases in current limiting control.

Depending on the control methods, the magnitudes of the inductance and the ripple voltage are in reverse relation. Why is this? The relation between the coil current and the voltage applied to both ends is expressed as

$$V = \frac{di_L}{dt} L \quad (1)$$

The peak coil current (I_{PEAK}) expressed with ON-time (t_{ON})

$$I_{peak} = \frac{V t_{on}}{L} \quad (2)$$

The energy (W) stored in the inductor can be calculated with the peak coil current and the inductance value

$$W = \frac{1}{2} L I_{peak}^2 = \frac{1}{2} \frac{(V t_{on})^2}{L} \quad (3)$$

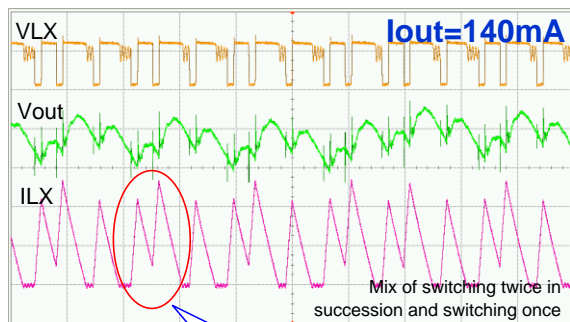
In the case of fixed ON-time PFM control, V and t_{on} in equation (2) are fixed, and thus I_{peak} is inversely proportional to L . According to equation (3), increasing L decreases W and a higher switching frequency is required to transmit the same amount of energy, so the ripple voltage that occurs in one switching operation decreases.

In current limiting PFM control, I_{peak} is constant, and thus according to equation (3), W increases in proportion to L . A larger amount of energy can be supplied in one switching operation, thus the switching frequency decreases and the ripple voltage of V_{out} increases.

Two types of coil current flow in PFM control

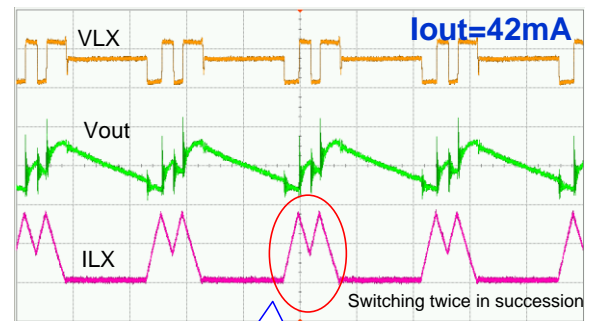
• Waveform when the output current is changed

As the load current is increased, the switching frequency changes and temporary continuous mode switching can be seen (Fig. 7). This happens when the output voltage does not recover to the set voltage or higher in one switching operation, and when a control method is used that performs switching continuously until the set voltage or higher is attained.



Switching takes place twice in succession, causing peak current to increase. Temporary continuous mode.

(a) Fixed ON-time PFM control (10 μ s/div)



Peak current is constant even when switching takes place twice in succession. Temporary continuous mode.

(b) Current limiting PFM control (2 μ s/div)

Fig. 7: In some cases a second switching takes place before the coil current returns to zero (V_{LX} : 5V/div, V_{out} : 50mV/div, I_{LX} : 200mA/div)

If the set voltage, or higher, is attained when switching is performed several times in succession, PFM control temporarily turns off switching operation.

Fig. 8 shows the waveform when the load current is gradually increased in current limiting PFM mode. Continuous switching appears, and as the load current is increased even further, the rapidity of the continuous switching increases, two or three times in succession in some cases, and the waveform is that of gradually increasing continuous switching and a rising switching frequency.

Because this is current limiting PFM control, the output current increases as the switching frequency increases, rather than as the coil current increases. When switching is performed in all ranges, the output current cannot increase any more.

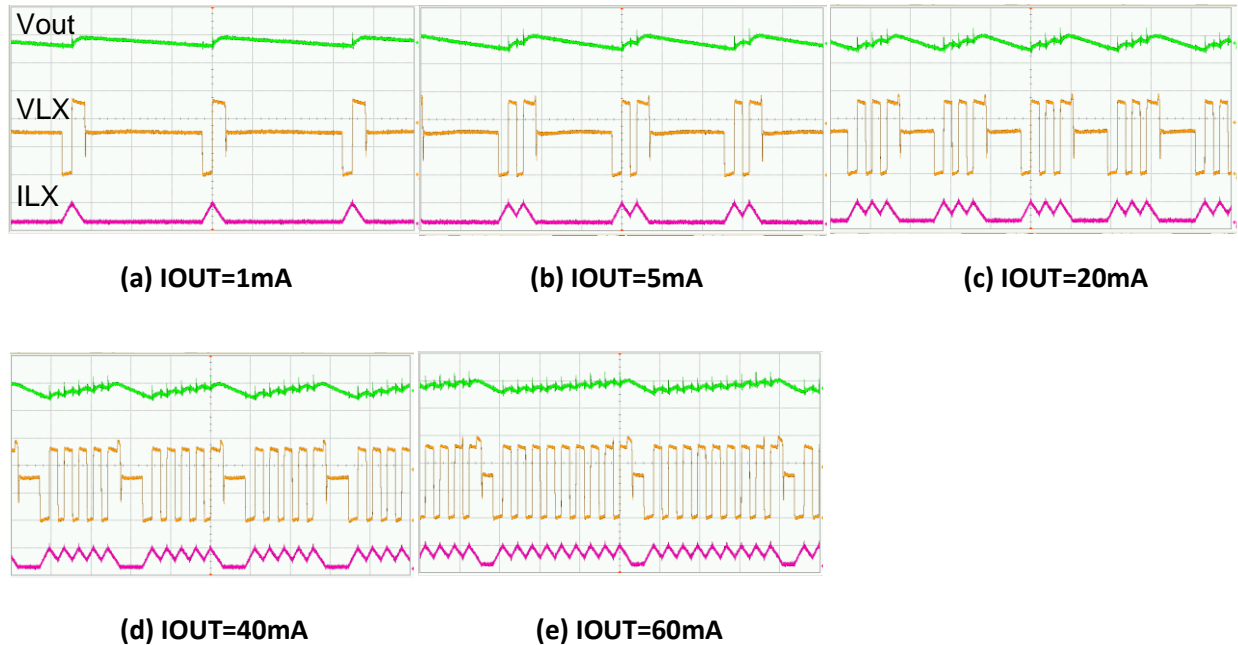


Fig. 8: Waveform when output current is changed in current limiting PFM control (V_{out} : 100mV/div, V_{LX} : 2V/div, I_{LX} : 500mA/div, horizontal axis 2 μ s/div)

The type where the frequency of continuous switching changes and the type where the frequency becomes shorter as in Fig. 3 are both called PFM control.

- **Operation is categorized by whether or not there is a zero coil current interval**

Non-continuous mode and continuous mode are terms that are frequently used to indicate the operating state of a DC-DC converter.

These states are not states that are intentionally selected. Switching between non-continuous mode and continuous mode takes place due to the dropout voltage, load current, and other conditions of the operating environment.

Non-continuous mode is an operating state wherein the energy stored in the coil due to switching is completely released prior to the next switching cycle and there is an interval during which the coil current is zero. As shown in Fig. 3, this state occurs noticeably at light loads in PFM control.

Continuous mode is an operating state where current always flows in the coil. This operating state occurs at large loads, when the dropout voltage is small, and during transient responses. Places where switching is continuous in Fig. 7 and Fig. 8 is due to temporary changes to continuous mode due to large loads.

The reason that names are given to operating states that change by themselves in response to the load is because there is a strong relation between ON-time and output current in non-continuous

mode, but almost no such relation in continuous mode, and thus a major difference exists in the states.

- **PFM is susceptible to ringing / Synchronous rectification is recommended**

When a DC-DC converter operates with an interval in which the coil current is zero (non-continuous mode), a ringing waveform may sometimes appear after switching, as shown in part (A) of Fig. 5.

This is due to resonance of the coil inductance and the parasitic capacitance of the wiring and/or Schottky barrier diode. This resonance occurs after the coil energy is released, and the coil end voltages appear to converge to the same potential.

In some synchronous DC-DC converters, the coil is monitored for completion of energy release, upon which the ends of the coil are shorted. This enables suppression of the ringing waveform, as shown in (B) of Fig. 6.

- **In continuous mode of PWM control, the ON-time barely changes even when the output current changes**

This is the first step in building a large-current circuit with a DC-DC converter power supply. When continuous mode of PWM control is understood, a large-current circuit can be built.

The waveform when the output current is gradually increased on a PWM control step-up DC-DC converter is shown in Fig. 9.

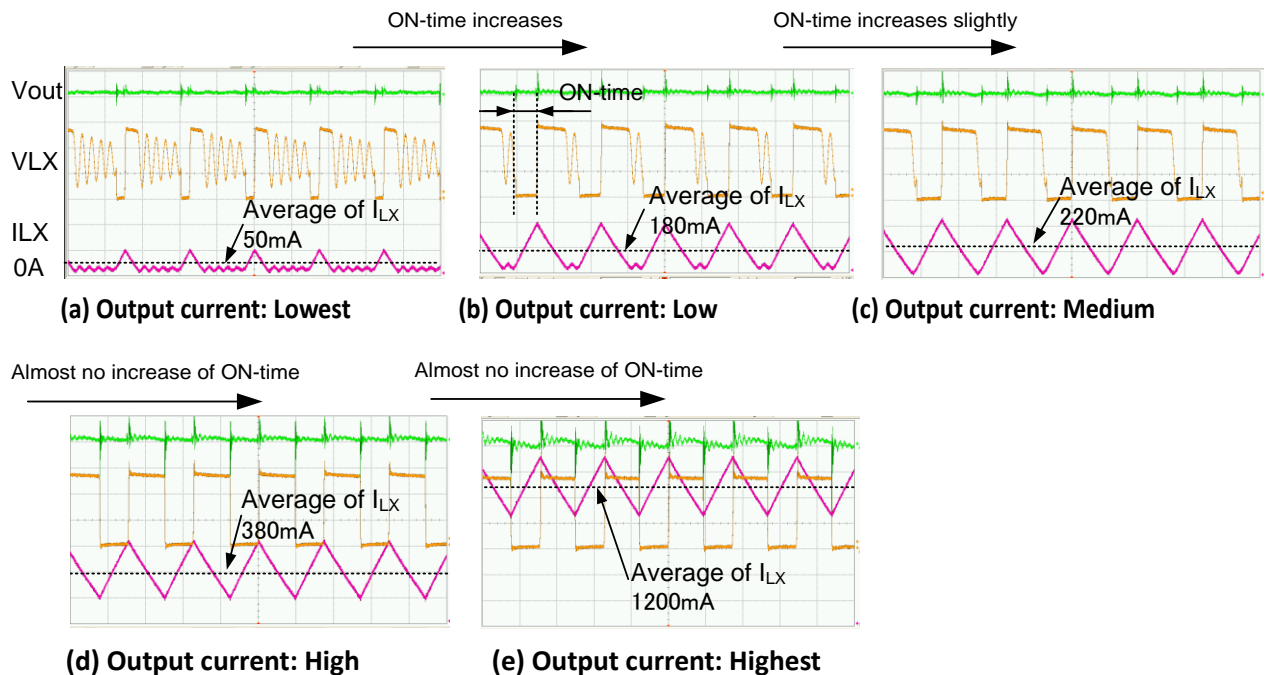


Fig. 9: Waveform when output current is changed in PWM control (V_{out} : 100mV/div, V_{LX} : 2V/div, I_{LX} : 200mA/div, horizontal axis 2 μ s/div)

If there is no current limiting, the current grows increasingly large in continuous mode. The I_{LX} current indicated here is the current that flows through the coil, not the output current. In the case of a DC-DC converter, the input power and output power become equal in the ideal model, and thus the output current can be approximately calculated from the inverse ratio of the input voltage and the output voltage (the actual thermal loss amount is added to the input current).

In continuous mode where the coil current does not become zero, there is almost no change in the duty-cycle.

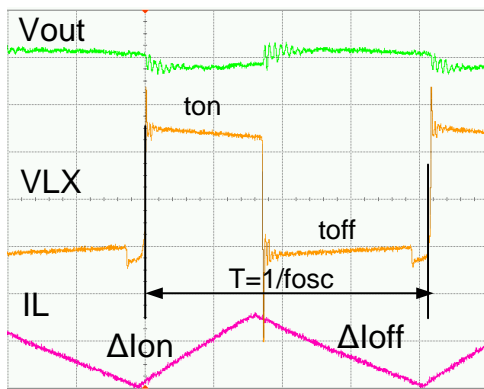
When the output current is small in non-continuous mode, the ON-time gradually lengthens as the current is increased. However, from a certain point, the lengthening of the ON-time almost completely stops.

When an even larger output current is drawn, the output voltage is maintained even though the ON-time barely changes. This state is continuous mode.

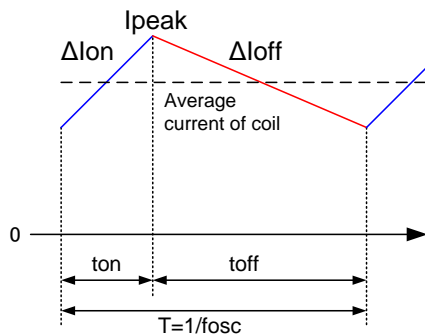
In continuous mode, the output current overlays the coil current. The point where the increase of ON-time stops is the boundary between non-continuous and continuous mode, and is called the boundary point.

● **The current flowing in the coil is a feature of continuous mode operation**

The relation between ON-time and OFF-time in continuous mode can be expressed as a simple equation of the input voltage and output voltage (Fig. 10). Because there is compensation for loss due to heat generation and other factors in reality, the ON-time is slightly longer than this ideal value.



(a) Waveform (V_{out} : 100mV/div, V_{LX} : 2V/div, I_L : 500mA/div, horizontal axis 200ns/div)



$$I_{peak} = \frac{\Delta V}{L} \cdot t_{on} \quad \Delta V: \text{Voltage at both ends of coil}$$

In continuous mode, the ratio of the ON-time and the OFF-time is expressed as the ratio of the input voltage and the output voltage. In actual operation, the ON-time is longer by the amount of the power loss.

Step-up DC-DC converter

$$\Delta I_{on} = \frac{V_{IN}}{L} \cdot t_{on} \quad \Delta I_{off} = \frac{V_{out} - V_{IN}}{L} \cdot t_{off}$$

$$\Delta I_{on} = \Delta I_{off}$$

$$\text{Duty} = \frac{t_{on}}{T} = \frac{V_{out} - V_{IN}}{V_{out}}$$

Step-down DC-DC converter

$$\Delta I_{on} = \frac{V_{IN} - V_{out}}{L} \cdot t_{on} \quad \Delta I_{off} = \frac{V_{out}}{L} \cdot t_{off}$$

$$\Delta I_{on} = \Delta I_{off}$$

$$\text{Duty} = \frac{t_{on}}{T} = \frac{V_{out}}{V_{IN}}$$

(b) Values and equations

Fig. 10: Relationship between input/output voltage and duty-cycle in continuous mode

A stable continuous mode is attained with both step-up DC-DC converters and step-down DC-DC converters. The change in coil current due to switching is controlled so that the energy stored during ON-time and the energy released during OFF-time is exactly equal. By maintaining this balance of energy storage and release, the output voltage can be kept stable.

The current that flows in the coil is the total of the DC current that is output and the average value of the switching current. The larger the DC current flowing in the coil, the larger the current that can be drawn. However, a coil with good DC overlay characteristics must be used.

Step-up ratio in continuous mode is limited

When a DC-DC converter operates in continuous mode, a large current can flow. However, caution is required with step-up DC-DC converters, as the step-up ratio is limited in continuous mode.

Like a step-down converter, the ON-time to OFF-time ratio depends on the relation between the input voltage and output voltage (Fig. 10).

In a step-up DC-DC converter, the energy stored in the coil must always be released to the output side, and thus a maximum ON-time per cycle is set in the control IC. Because of this, the duty-cycle is limited (Fig. A). If the step-up ratio requires a higher duty-cycle, operation in continuous mode will not be possible, and drawing too much current will prevent the required voltage from being obtained.

If step-up operation in excess of this ratio will be performed, the control method (fixed ON-time, fixed OFF-time, current limiting, etc.) and coil value must be selected so that operation is in non-continuous mode even at maximum output current.

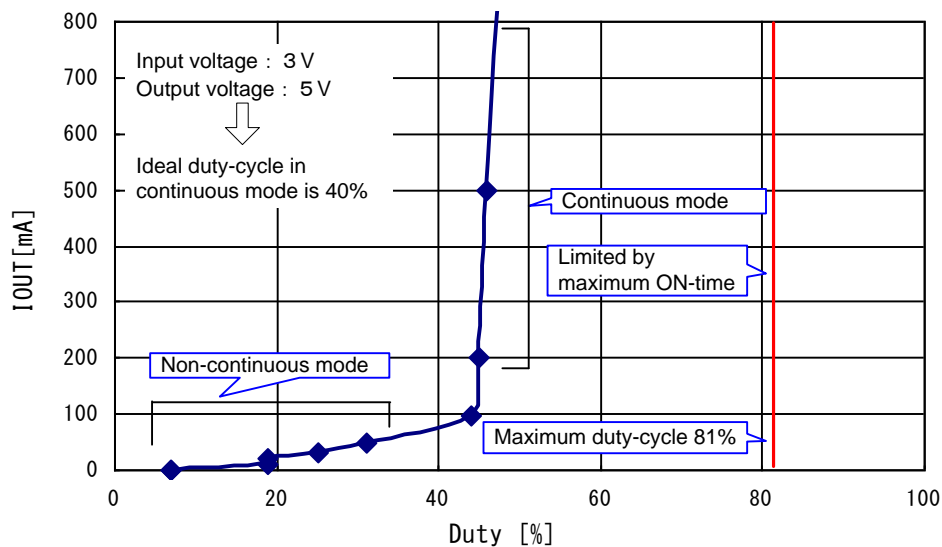


Fig. A: ON-time and maximum duty

Auto switching between PFM and PWM for constant high-efficiency

Let's look at the transient response of the output current when a step-down DC-DC converter is created with a function for automatic switching between PFM control and PWM control as shown in Fig. 11.

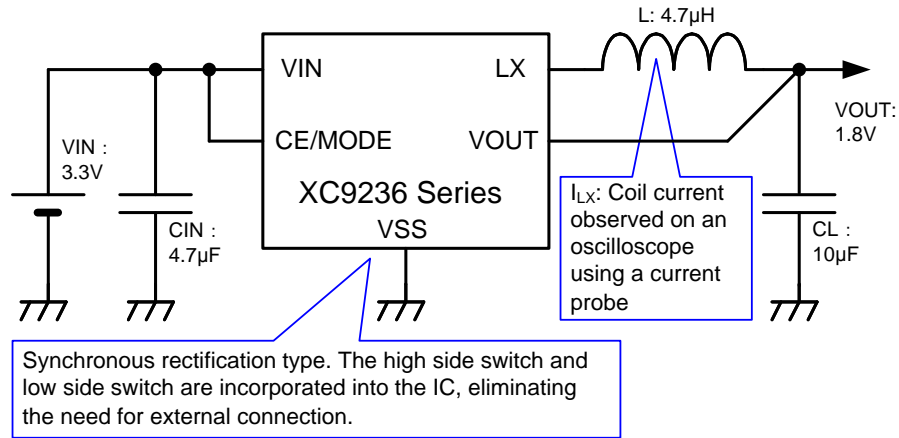


Fig. 11: Step-down DC-DC converter of PFM/PWM auto switching control

Operation during the change from PFM control to PWM control, and during the change from non-continuous mode to continuous mode, can be observed in Fig. 12. The PWM/PFM auto switching function uses PFM control, which has good efficiency, for operation at light loads. As the output current increases, the PFM switching frequency increases, and when it reaches the same frequency as the PWM switching frequency, the function automatically switches to PWM control. In operation by PWM control, the ripple voltage is small when the output current is large, and a large current can be output with stability even in continuous mode. In this way, the PWM/PFM auto switching control IC achieves high efficiency and low ripple voltage no matter whether the load is light or a large current is drawn.

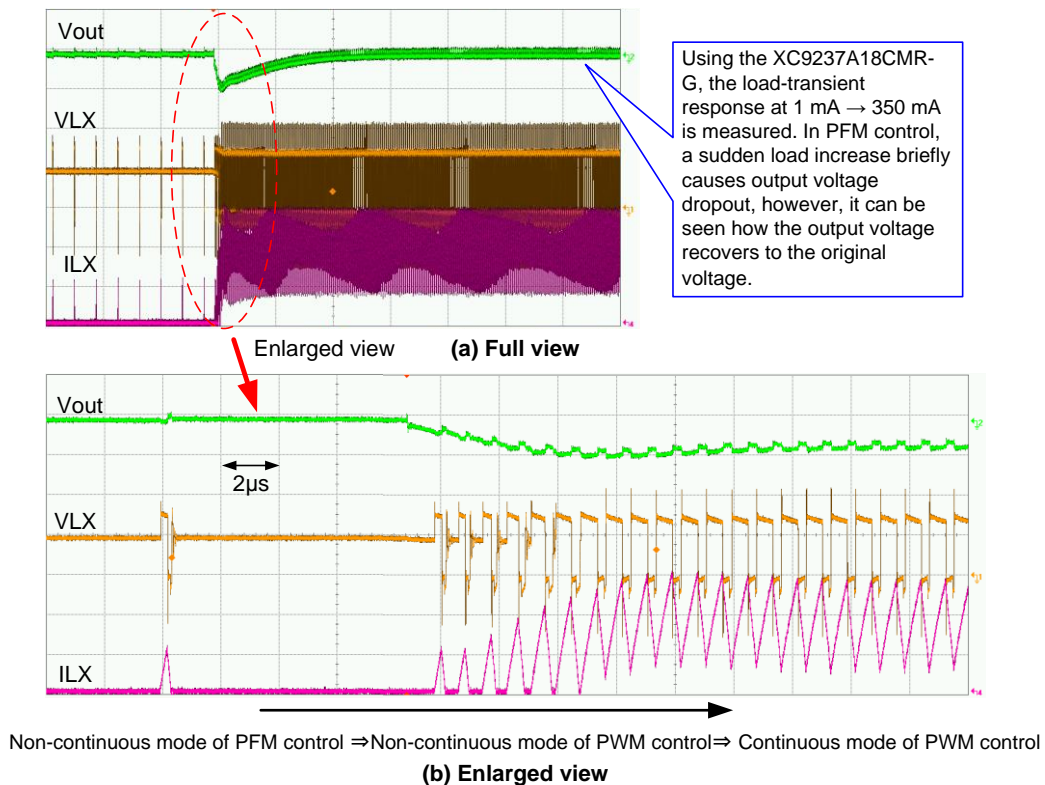


Fig. 12: Change of control method and operation mode when output current changes with step-down DC-DC converters

Synchronous DC-DC converter efficiency is checked with the “horns”

In order to check if synchronous rectification is operating efficiently, the operational waveform can be analysed. With synchronous rectification operation of a step-down DC-DC converter, continuous switching between ON and OFF of the high side switch and low side switch takes place. To prevent the high side switch and low side switch from switching ON simultaneously, an OFF interval for both switches is set in the switching timing. The actual waveform shows the characteristic horn-shaped waveform, which is indicated in Fig. B. The coil current flows through the MOSFET parasitic diode at this time. However, a voltage difference occurs in the forward voltage of the diode (about 0.6V), and a power loss equal to the current multiplied by the voltage difference occurs. In the operation of the synchronous rectification circuit, power loss is held down by the low ON resistance MOSFET switch turning ON, and thus a shorter “horn” time results in a higher efficiency.

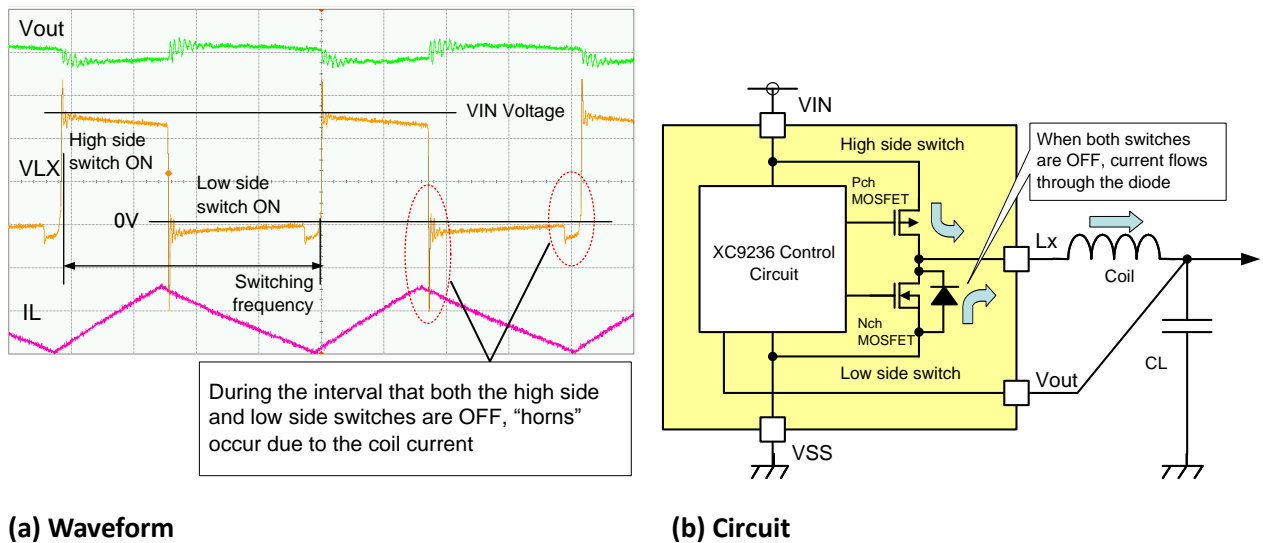


Fig. B: Operational waveform of synchronous rectification

Noise must be stopped at the source

Diodes and MOSFETs

As shown in Fig. 13, there are a variety of methods for reducing DC-DC converter switching noise. The waveform of a step-up DC-DC converter in which noise is reduced using a ferrite bead is shown in Fig. 14. By inserting a ferrite bead after the Schottky barrier diode, spike noise in the output voltage can be reduced. Although output voltage noise is reduced, it appears that noise during L_x turn-off increases.

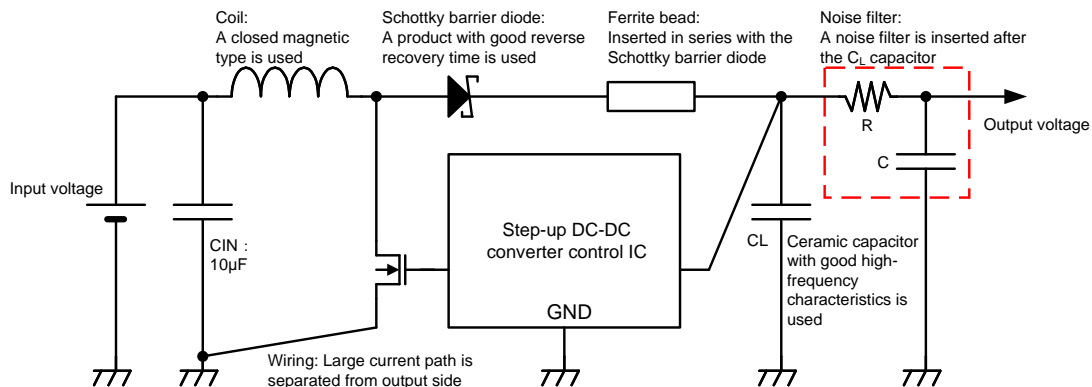


Fig. 13: Switching noise reduction method

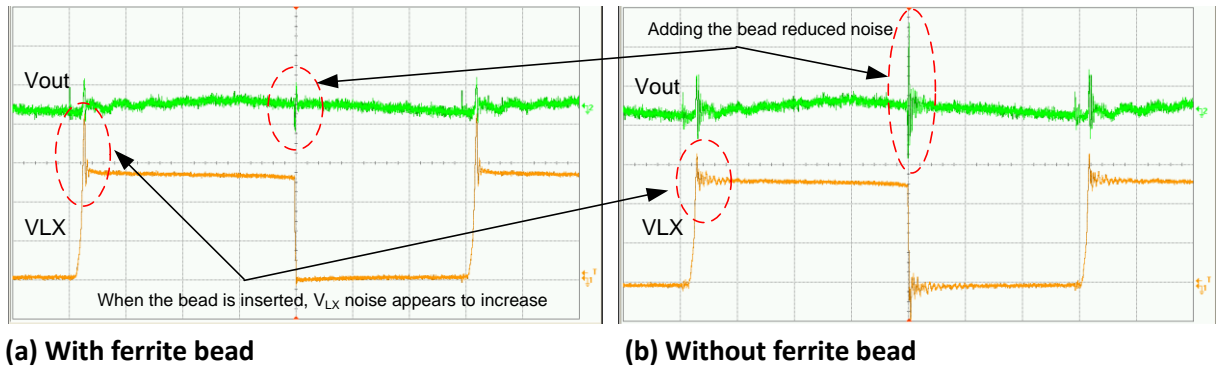


Fig. 14: Difference in noise when ferrite bead is inserted and not inserted (V_{out} : 50mV/div, V_{LX} : 2V/div, horizontal axis 500ns/div)

• MOSFET

When an external MOSFET type DC-DC converter similar to that in Fig. 15 is used, a MOSFET with low ON resistance generally allows easy reduction of power loss and an increase of efficiency.

In this case, attention must be paid to the gate capacitance of the MOSFET. During switching, driver transistor gate voltage changes will operate in reverse phase with the voltage of the drain pin of the external MOSFET. A sudden fluctuation of drain pin voltage will couple with the drain and gate capacitance of the MOSFET and destabilize the gate voltage. When the gate voltage oscillates, the MOSFET cannot be turned ON or OFF suddenly and the change in drain current appears as output noise in the drain pin voltage. Unwanted current flow will also occur during that time, decreasing power efficiency.

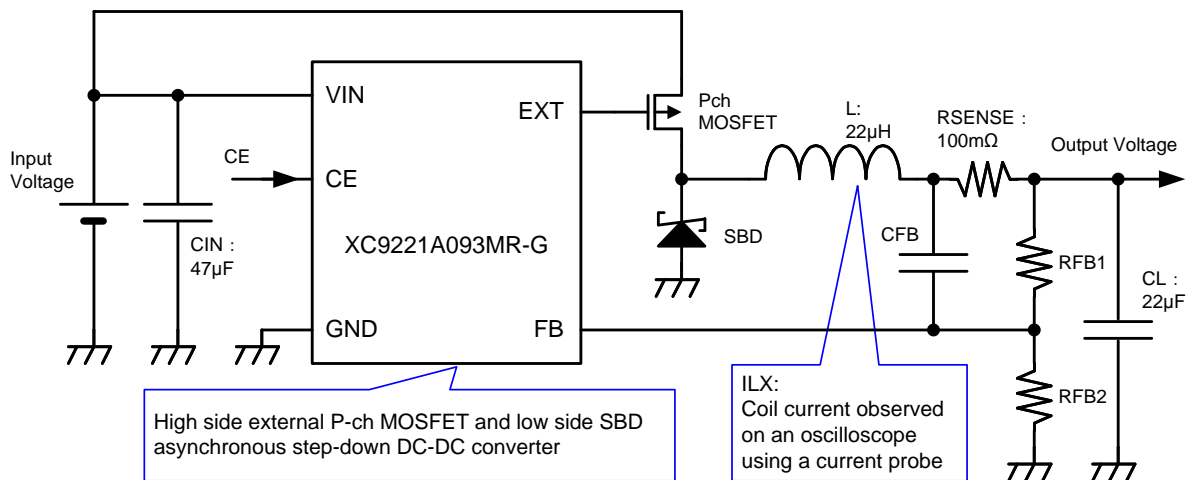


Fig. 15: Step-down DC-DC converter that switches external P-ch MOSFET

If you want to use a low ON resistance MOSFET with a large gate capacitance when handling a large current, noise can be reduced by using a bootstrap control IC. An example of a DC-DC converter that uses a bootstrap control IC is shown in Fig. 16.

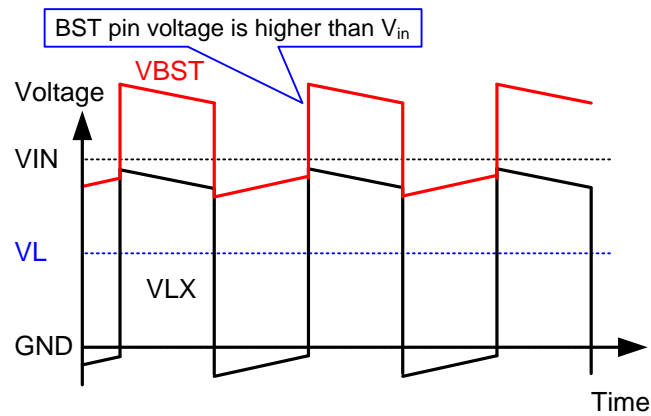
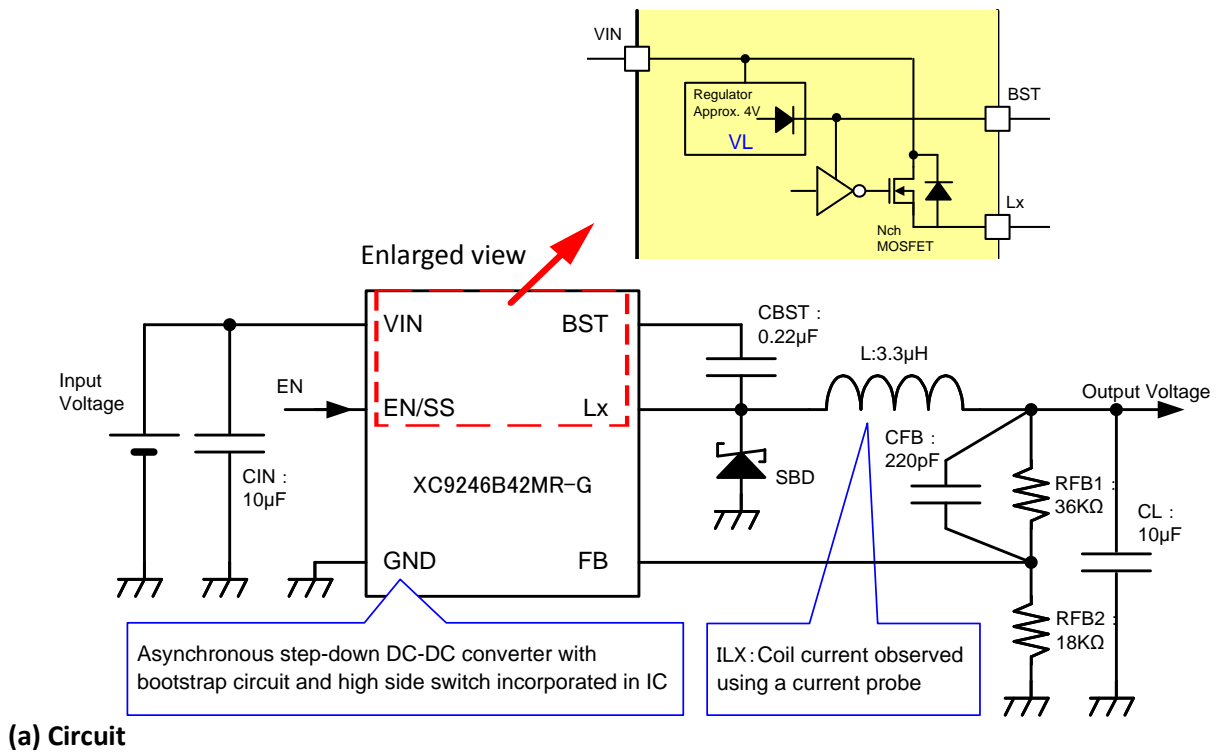
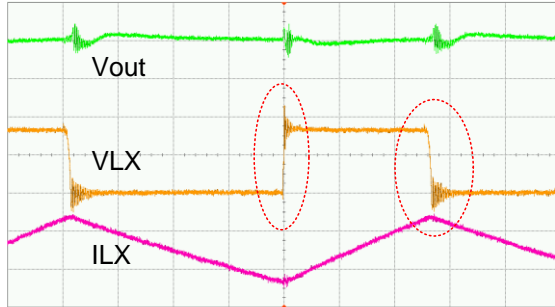


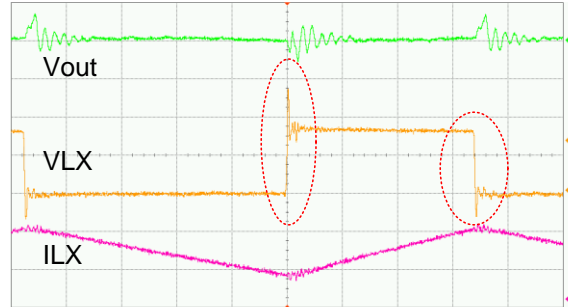
Fig. 16: Step-down DC-DC converter that switches N-ch MOSFET by bootstrap

With the bootstrap method, an N-channel MOSFET is used for the high side switch. When the high side switch turns ON, the source voltage and gate voltage of the N-channel MOSFET of the high side switch, which is also the end of the coil, operate in phase, and the gate voltage does not oscillate even when a sudden change of coil current occurs. For this reason, the waveform during switching is relatively well behaved (Fig. 17).



Using an optimum high side P-ch MOSFET, substantial noise does not occur

(a) XC9220 Series that drives P-ch MOSFET (Fig. 15, V_{out} : 100mV/div, V_{LX} : 5V/div, I_{LX} : 200mA/div, horizontal axis 500ns/div)



An N-ch MOSFET is used in the bootstrap circuit, and thus noise is suppressed even at large current

(b) XC9246 Series that drives N-ch MOSFET by bootstrap (Fig. 16, V_{out} : 100mV/div, V_{LX} : 5V/div, I_{LX} : 500mA/div, horizontal axis 500ns/div)

Fig. 17: Differences in switching noise by MOSFET drive method (V_{out} : 100mV/div, V_{LX} : 5V/div)

However, to drive the gate of the N-channel MOSFET of the high side switch, a voltage higher than the input voltage for operation of the control IC is needed, and thus a charge pump circuit must be added and the number of components increases.