1.Necessity and Application of Low Ripple in DC/DC Converters

■ **Power configuration linear regulator or DC/DC converter?**

When considering the power configuration for a device, do you ever have difficulty deciding whether to use a linear regulator or a DC/DC converter? If the LSI operating voltage drops to 1.8 V or 1.2 V, using a linear regulator for the drive from a 5 V line or lithium battery will result in a large thermal loss and power cannot be used efficiently. In this type of situation, it is well known that using a step-down DC/DC converter permits highly efficient voltage conversion. However, using a DC/DC converter raises many concerns, such as the generation of an excessive amount of noise, increased cost due to additional external components, and the complexity of setting various constants.

This edition of Application Notes will help you understand the basic features and operation of DC/DC converters through an explanation of the operation of the Torex XC9235/XC9236/XC9237 Series of DC/DC converters. The XC9235/XC9236/XC9237 are all-in-one DC/DC converters that require few external components and no adjustment of constants. The dual achievement of low noise and high conversion efficiency makes these ICs a popular choice for wireless device applications.

2.Features of XC9235/XC9236/XC9237 Step-Down DC/DC Converter ICs

Recent step-down DC/DC converters require few external components, and many products have been released that feature easy operation by simply adding a coil and capacitors. Such DC/DC converters provide a highly efficient power source, while only requiring one additional small coil compared with LDO regulators.

■ XC9235/XC9236/XC9237 Series

Torex XC9235/XC9236/XC9237 Series of step-down synchronous rectification-type DC/DC converters integrate two MOSFETs (one N-channel and one P-channel) to supply the output current. Circuit constants required for stable operation are set within the IC, and the only external components needed by these all-in-one DC/DC converters are the input and output capacitors and a coil indicated in the datasheet. An output current of up to 600 mA can be supplied. (See Fig. 1)

Fig.1: XC9235/XC9236/XC9237 Series Standard Circuit

XC9235/36A, B, C, E, G (3 MHz product)
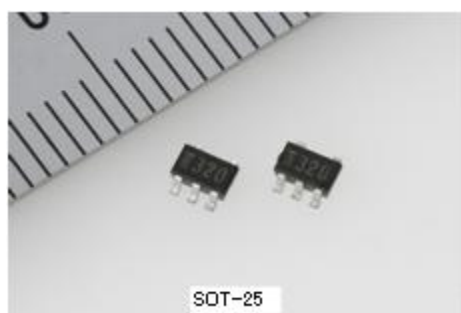**(Torex Semiconductor)**
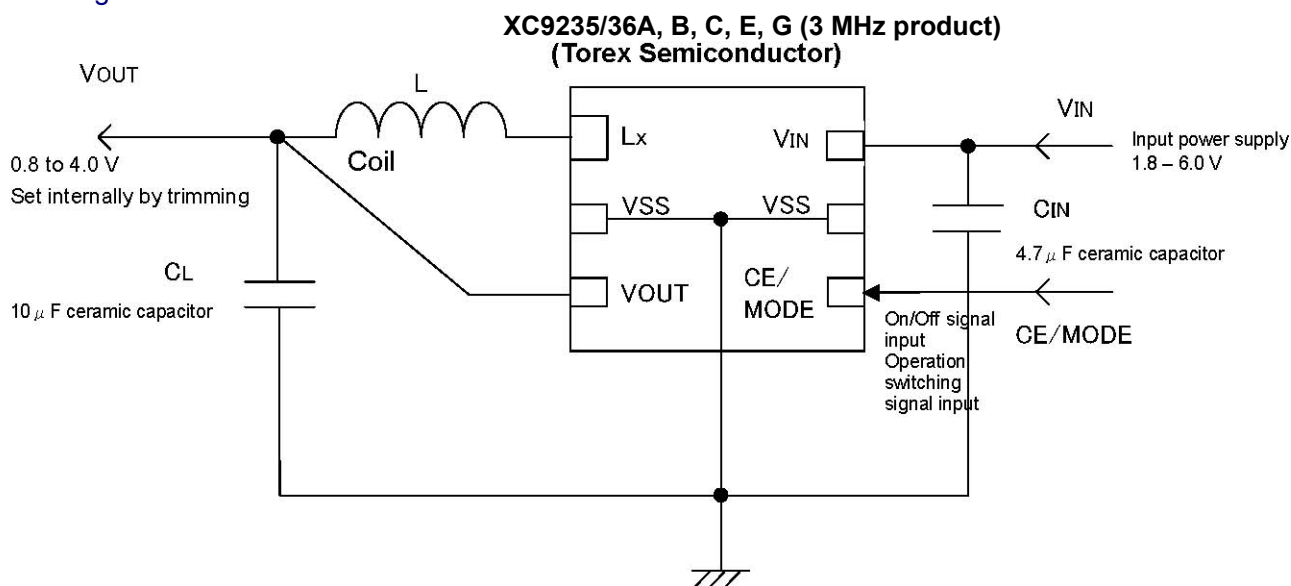
The control method of this IC varies by model number. The XC9235 uses PWM control, the XC9236 operates in PWM/PFM auto switching control, and the XC9237 permits to select manually between PWM/PFM auto switching control and PWM control. You can select between two switching frequencies, 1.2MHz for applications where higher efficiency is desired, and 3MHz which permits the use of a smaller coil, thus providing a smaller overall solution. A wide variety of functions and optional of features are available to meet the needs of your application.

The high-speed soft-start and C_L discharge features enable respectively quick starting and stopping at on/off, which is convenient when building the power sequence of the set.
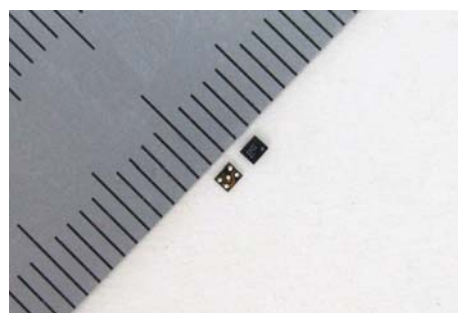
Table 1: XC9235/XC9236/XC9237 Options

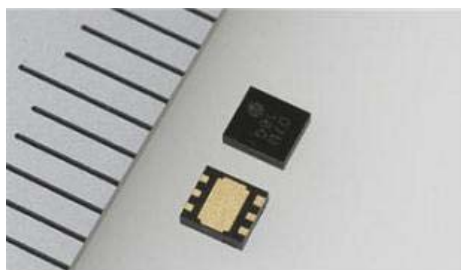| Output Voltage	Type	Operating Voltage Range	Description
Fixed output voltage	A		No C_L high-speed discharge
(V_{OUT} product)	B	2V to 6V	C_L high-speed discharge, high-speed soft start
	C		C_L high-speed discharge
	E		C_L high-speed discharge
	G	1.8V to 6V	C_L high-speed discharge, high-speed soft start
External output voltage	D		C_L high-speed discharge
setting (FB product)	F		C_L high-speed discharge, high-speed soft start

Packages are SOT-25, USP-6C (2.0 mm×1.8 mm, t = 0.6 mm MAX) and

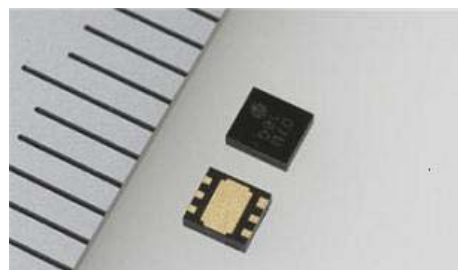USP-6EL (2.0 mm×1.8 mm, t = 0.4 mm MAX), WLP-5-03(1.26mm×1.06mm, t=0.4mm).

SOT-25

WLP-5-03

USP-6EL
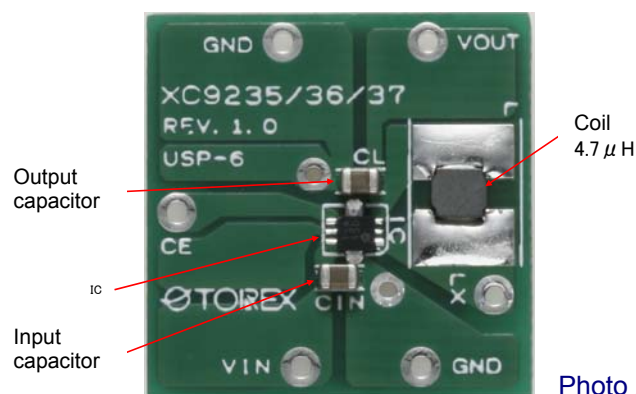

USP-6C

Photo 1: Package Photo

Photo 2: Mounting Board Photo

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Fig. 2: Internal Block Diagram of the XC9235/XC9236/XC9237

The internal circuitry includes the reference voltage, error amplifier, oscillator, ramp waveform, PWM comparator, UVLO, and current limit circuit. In the fixed output voltage type, the internal resistance ratio R_1/R_2 is adjusted by laser trimming. The operating voltage range is 1.8 V to 6 V. The amplifier phase correction, transmission frequency, and soft-start time are adjusted internally, allowing the product to be used without any adjustments.

3.Testing Using the XC9235/XC9236/XC9237 and Methods of Use

■ **PWM/PFM Auto Switching Operation Reduced loss**

One of the key reasons for using a DC/DC converter is the expected high power conversion efficiency. Efficiency is improved by reducing losses. As shown in Fig. 3, the main causes of loss are the supply current of the IC, thermal loss due to the on-resistance of the driver transistor, and loss due to the serial resistance of the coil.

Fig. 3: Main locations of power loss in a step-down DC/DC converter
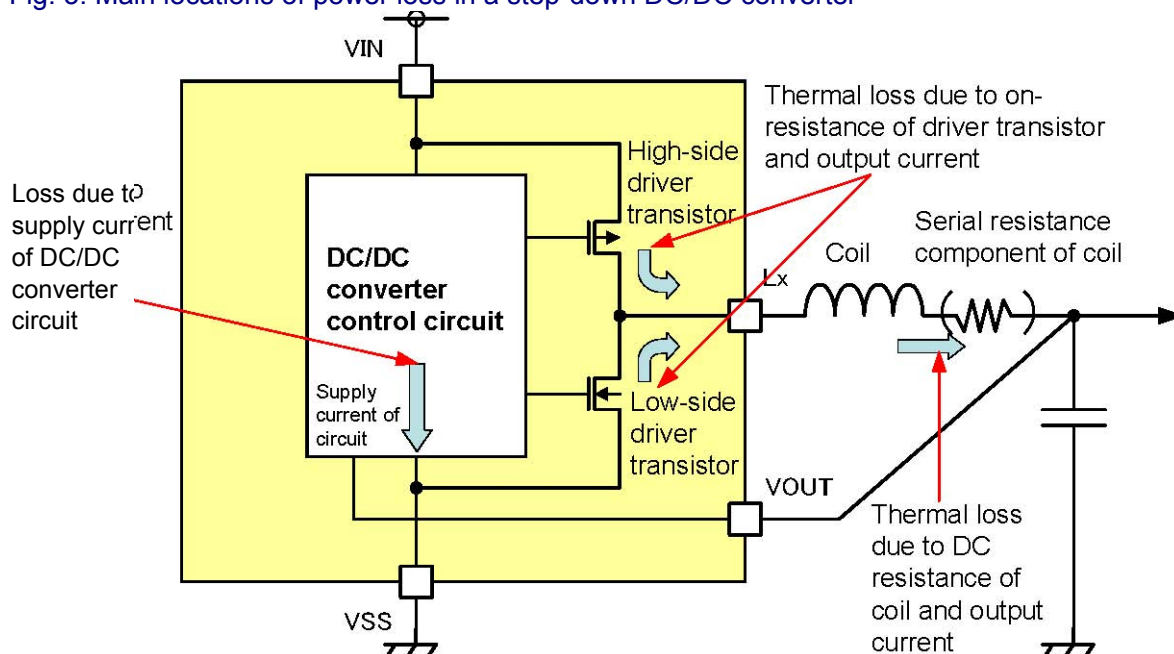
To improve efficiency when the load is light, it is important to reduce the supply current of the IC The key to this is the IC control method.

PFM control and PWM control

When the load current is light, PFM control reduces the number of switching cycles per unit time reducing ineffective current such as supply current and through current and thereby improving efficiency. PFM holds quiescent current down to 15 μA in the IC when there is no load. When the load current is large, the supply current of the IC is negligible, and thus PWM control with its smaller ripple voltage is better suited.

PWM/PFM Auto Switching Control

The XC9236 has a feature that automatically switches between PFM and PWM control depending on the load. This feature makes it possible to achieve both high efficiency at light loads and low ripple at heavy loads, contributing to high efficiency across a full range of loads. (See Fig. 4)
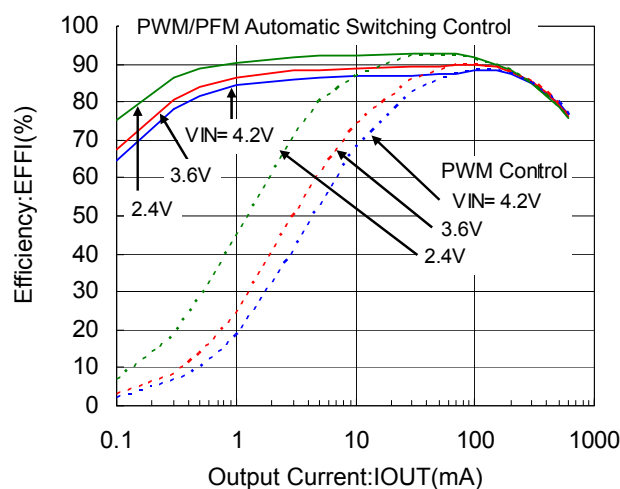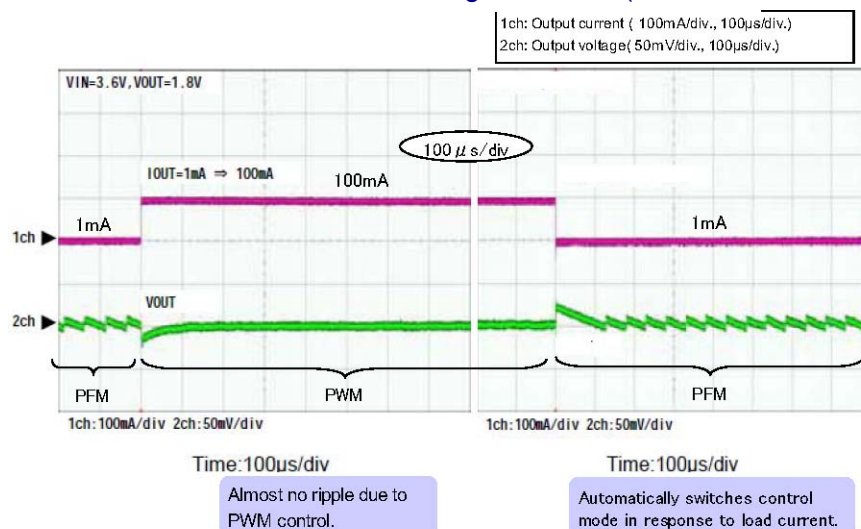
Fig. 4: Power Conversion Efficiency

Fig. 5 shows the load transient response when switching from PFM control to PWM control and from PWM control to PFM control.

Fig. 5: PFM Control and PWM Control Auto Switching Waveform (load current： 1 mA ⇔ 100 mA)

The fast response of the IC is visible during steep load transients, because the output voltage starts recovering after dropping by only 20mV. Moreover, here should read there to be sufficient phase margin because overshoot and ringing do not occur during recovery.

Manual switching

In addition to PWM/PFM auto switching, the XC9237 type has a feature that forcibly fixes control at PWM control by means of an external signal. This makes it possible to switch to lower-ripple PWM control based on the operational conditions of the devices, enabling timely control of noise reduction. (See Fig. 6-1 and Fig. 6-2)

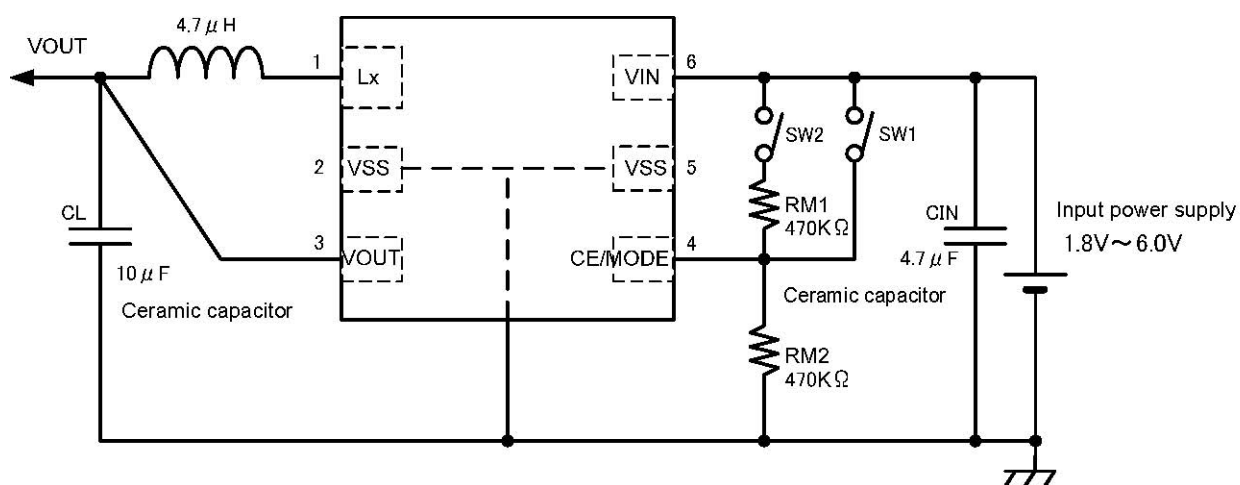Fig. 6 -1: XC9237 PWM/PFM Control Manual Switching Circuit Schematic

Fig. 6-2: XC9237 PWM/PFM Switching

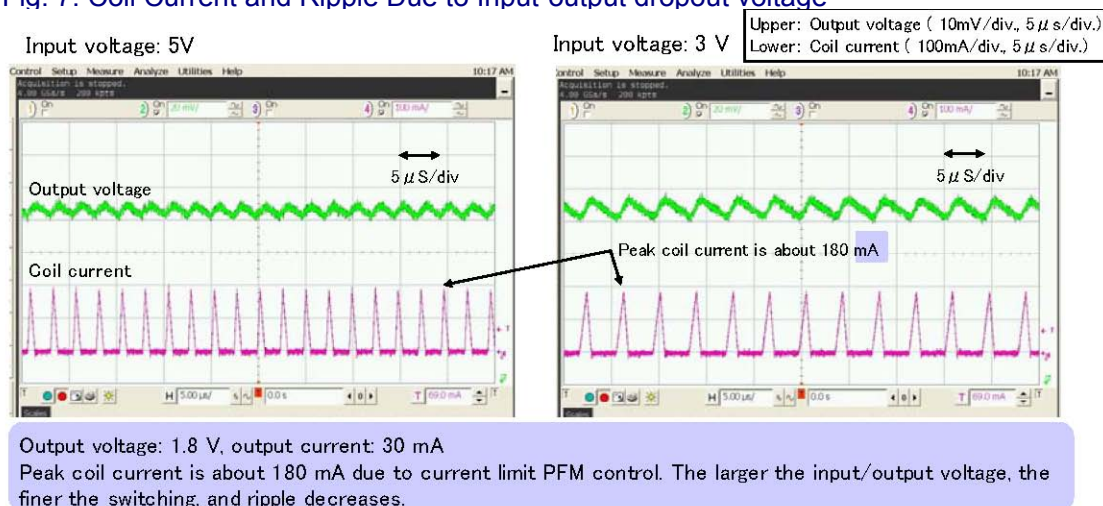| SW1	SW2	State
ON	-	PWM/PFM auto switching control
OFF	ON	PWM control
OFF	OFF	Standby

Basics of DC/DC Converters

■ Current limiting PFM Control

Features of current limiting PFM

Current limiting PFM control is used for PFM control in this IC, making it easy to meet the need for low-voltage operation and low ripple in LSIs used in small portable devices. Current limiting PFM control is a control method whereby switching is turned off when the current flowing in the coil reaches a constant value (180 mA).

With fixed-duty PFM, the coil current due to switching grows large when the input-output dropout voltage is large, and therefore ripples tend to be large. By contrast, a feature of current limit PFM is that the on-time is shorter and the coil current is smaller when the input-output dropout voltage is large, and thus ripple is smaller as shown in Fig. 7.

Fig. 7: Coil Current and Ripple Due to Input-output dropout voltage

Output voltage: 1.8 V, output current: 30 mA
Peak coil current is about 180 mA due to current limit PFM control. The larger the input/output voltage, the finer the switching, and ripple decreases.

When the operating voltage of the LSI supplied by the DC/DC is even lower than 1.8V (for example, 1.5V or 1.2V). The specifications for the, output voltage accuracy and low ripple may become even tougher.

Maximum on-time restriction

The maximum on-time in PFM is also determined. When the input voltage and output voltage are close and the input-output dropout voltage is extremely small, or when 180 mA is not to be reached even though switching is on and current flows through the coil, switching is temporarily turned off by the maximum on-time restriction (which corresponds to the duration of two oscillation cycles) to prevent excessive on time.
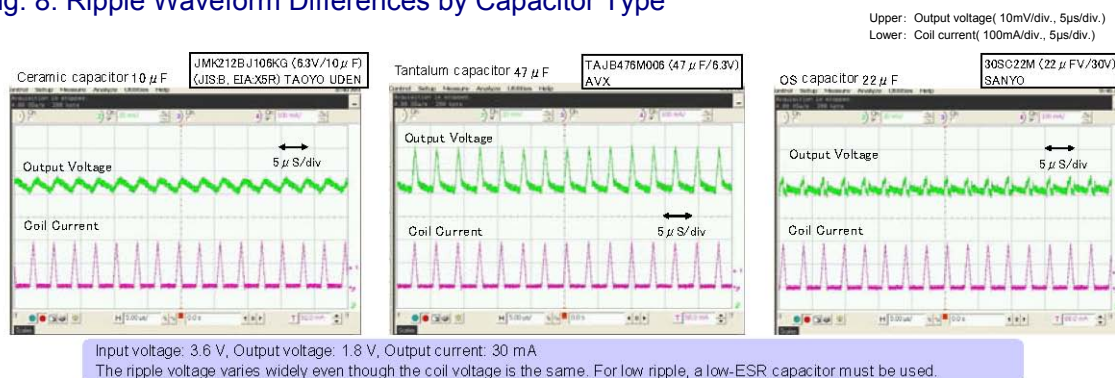
Basics of DC/DC Converters

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<< Ripple noise and spike noise >>

The types of noise that occur in DC/DC converters can be broadly divided into ripple noise and spike noise.
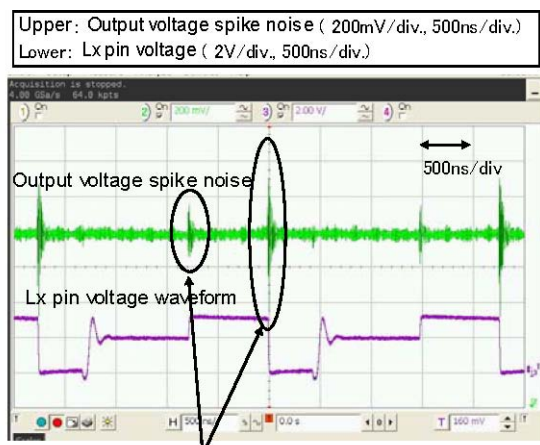
Ripple noise

Ripple noise is caused by the ESR (Equivalent Serial Resistance) of the capacitor and direct current when the coil current due to switching and the current energy stored in the coil are released to the load capacitor. The amount of noise varies widely depending on the type of capacitor. When a high-ESR tantalum capacitor or electrolytic capacitor is used, the ripple noise is large. When a low-ESR capacitor such as a ceramic capacitor is used, the ripple is small and takes the shape of a waveform similar to a sine wave. (See Fig. 8)

Fig. 8: Ripple Waveform Differences by Capacitor Type

Input voltage: 3.6 V, Output voltage: 1.8 V, Output current: 30 mA
The ripple voltage varies widely even though the coil voltage is the same. For low ripple, a low-ESR capacitor must be used.

Measurement techniques for high-frequency noise

Spike noise is high-frequency noise caused by the switching timing, and is mainly due to the driver transistor having a steep turn-on and turn-off slope. Care is required when measuring spike noise. The wrong type of measurement circuitry will prevent correct measurement.

Fig. 9: Spike Noise Waveform

Spike noise
Occurs due to the switching timing. High frequency of several tens of MHz, amplitude of several hundreds of mV.

Attention must be paid in particular to ground connections around the probe. To prevent noise from being picked up while probing, the probing ground should be disconnected and the probing pin should be directly connected to the measuring pin over the shortest distance. In addition, a typical mistake is to test with the high-frequency filter of the tester switched on. DC/DC converter spike noise is high-frequency noise from 20 to 50 MHz, and thus leaving the high-frequency filter on naturally prevents measurement. (See Fig. 9)

■ Application circuit for variable output voltage operation

By adding a resistor and connecting the FB pin option of this series to a DA converter or Nch open drain, a variable output voltage circuit can be created as shown in Fig. 10.

Fig. 10: Variable Output Voltage Circuit Using a DAC
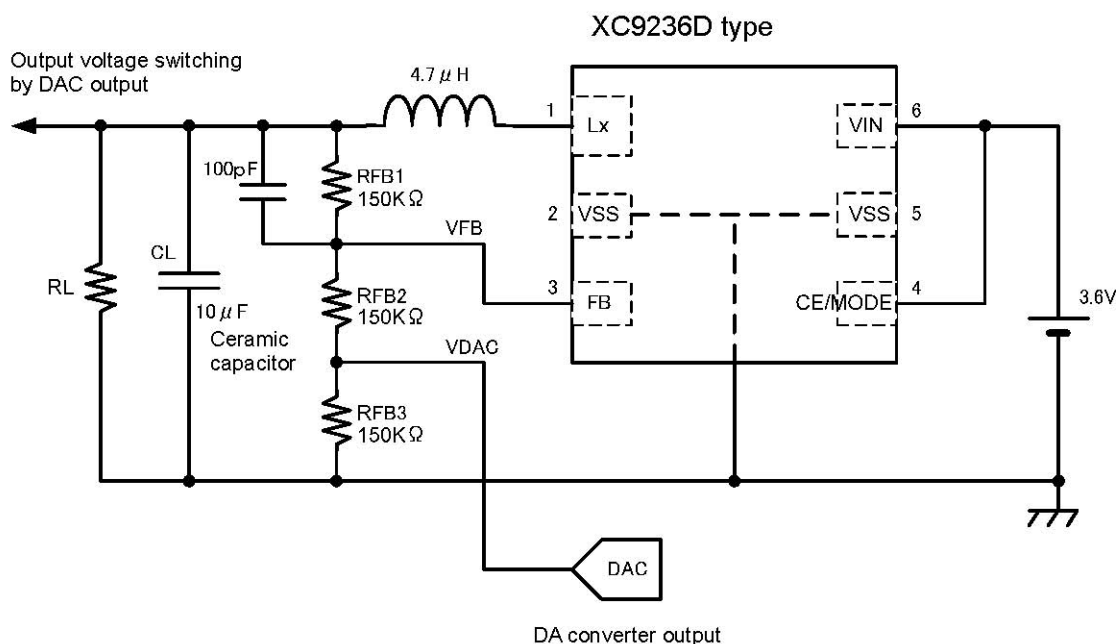
This is a convenient method for adjusting voltage in response to the operating conditions of a microprocessor other device. The FB pin voltage (V_{FB}) is 0.8 V and is configured to receive feedback. The output voltage using a DAC is determined by

$$V_{OUT}＝(V_{FB}－V_{DAC})(R_{FB1}／R_{FB2})＋V_{FB}$$

Graph 1 shows the relationship between V_{OUT} and V_{DAC}.

Graph 1: DAC Voltage vs. Output Voltage
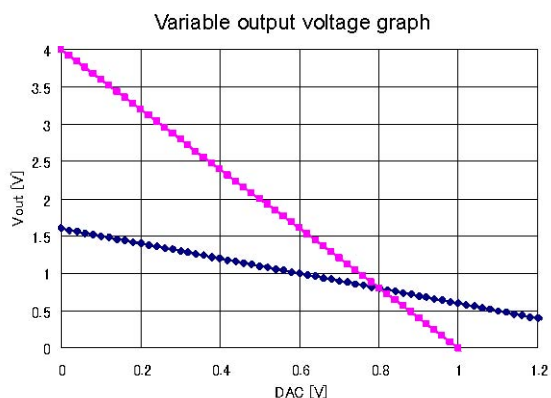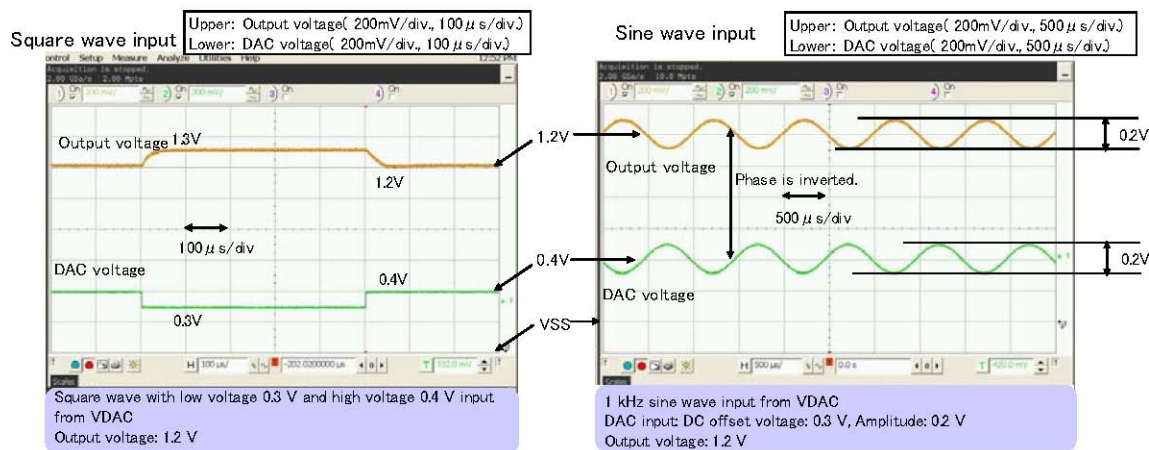
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Fig. 11 shows an evaluation of tracking by V_{OUT} of DAC output when a square wave and sine wave are input.

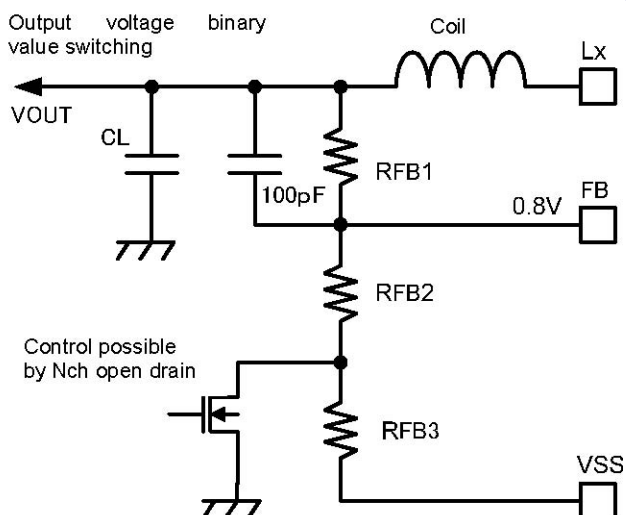Fig. 11 Output Voltage Tracking of Changes in DAC Voltage 1 (Square Wave, Sine Wave)

If the output voltage is a binary value voltage, it is convenient to use an Nch open drain. (See Fig. 12)

When Nch open drain is on, $V_{OUT} = 0.8V \times (R_{FB1}+R_{FB2})/R_{FB2}$

When Nch open drain is off, $V_{OUT} = 0.8V \times (R_{FB1}+R_{FB2}+R_{FB3})/(R_{FB2}+R_{FB3})$

Fig. 12: Binary-Value Switching Circuit Using an Nch Open Drain

4. Low Ripple Technology

■ Achieving low ripple during PFM/PWM auto switching

The key feature of this IC is low ripple voltage when switching from PFM to PWM control. As the load changes from light to heavy, the PFM pulse interval gradually becomes shorter and more frequent. When the frequency of PWM control is finally reached, control changes to PWM. However, with previous products such as the XC9226, it is not possible to generate a properly dispersed pulse before switching to PWM control, and a group of pulses is occasionally generated. (See Fig. 13)

Fig 13: Repeated Pulse Waveform in the XC9226 Series
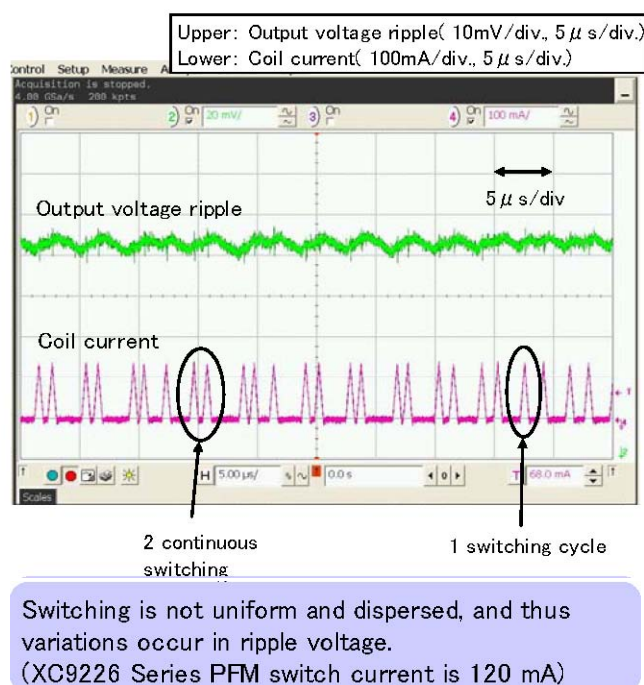
In PFM control, switching takes place when the load current grows large and the output voltage falls. If the output voltage does not recover after switching is performed once, switching is performed a second time. If the output voltage still does not recover, switching is performed a third time. Switching continues in this way until the output voltage recovers, and as a result localized coil current overlay occurs and may cause a large ripple in the output. Switching is performed intermittently in PFM, and thus even if the current is not dispersed evenly through the coil and localized overlay occurs, balance is maintained between the output current and the output voltage.

Basics of DC/DC Converters

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By contrast, switching takes place at a constant interval in PWM control, and thus the current in the coil must be balanced to a constant current and dispersed.

PWM/PFM auto switching control in the XC9236 Series dramatically reduces the occurrence of this localized grouping, and by effecting a continuous transition from PFM control to PWM control while maintaining a dispersed and balanced current, achieves low ripple across the entire load range as shown in Fig. 14.

Fig. 14: XC9236 Ripple vs. Load Current / Coil Current Graph

Input voltage: 3.6 V, Output voltage: 1.8 V

(1) Operates on one switching cycle
(2) Load current is large, but there is no continuous switching; operates on 1 uniform switching cycle.
(3) Load current is even larger and is close to PWM control frequency, but operates on 1 uniform switching cycle.
(4) Switches to PWM control.
Coil current overlay occurs.

Upper: Output voltage ripple(10mV/div., 1 µs/div.)
Lower: Coil current(100mA/div., 1 µs/div.)

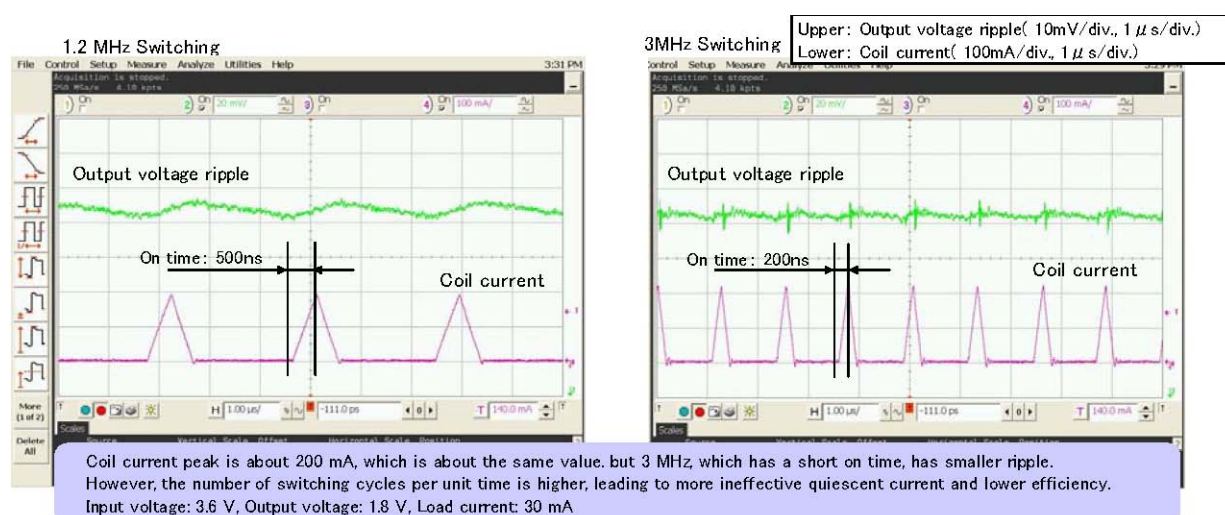Output current =10mA   Output current=50mA   Output current=100mA   Output current=200mA

<< **Selecting the switching frequency involves a tradeoff between size reduction and low power consumption** >>

Rapid switching frequency may be undesirable in a DC/DC converter. The key point is to select a switching frequency that matches the priority.

It is expected that a DC/DC converter has a high power conversion efficiency, and thus a low on-resistance MOSFET is often used for the transistor in a current driver. The drive method of a MOSFET is a capacitive gate drive, and thus charging and discharging of the gate are repeated with each switching. In general, the lower the on-resistance of the MOSFET, the higher the capacitance of the gate. As such, the higher the switching frequency (as in Fig. 15), the higher the number of cycles, and this increases ineffective quiescent current and through current, resulting in poor efficiency. If efficiency is important, it is best to select a slower frequency.

Fig. 15 Switching Frequency vs. Coil Current and Ripple

Coil current peak is about 200 mA, which is about the same value. but 3 MHz, which has a short on time, has smaller ripple. However, the number of switching cycles per unit time is higher, leading to more ineffective quiescent current and lower efficiency.
Input voltage: 3.6 V, Output voltage: 1.8 V, Load current: 30 mA

One advantage of selecting a high switching frequency is smaller components. A higher frequency allows a lower inductance to be set for the coil, and this means a lower number of turns and a smaller body size can be selected. Fewer turns mean a smaller serial resistance, and even if the same size is used, the wire gauge can be larger resulting in a lower serial resistance component and better power efficiency.

When selecting a coil, attention must be paid to the overlay characteristics. For example, if an output current of 200 mA is required, the peak current flowing through the coil will reach 300 mA (Fig. 14-4). If the coil has a poor overlay characteristic, the coil current slope will be steeper and the peak current will increase. This may cause more ripples and the activation of current restriction, and thereby affect phase control. It is best to select a coil with sufficient leeway in the overlay characteristic.

Reference materials
1. Torex Semiconductor Ltd. TIP (Technical Information Paper) No. 00006
   "Testing Spike Noise and Reduction Methods"