Smart Analog IC 300

How to measure and correct the gain error and offset voltage

Introduction

This application note describes how to measure and correct errors (gain errors and offset voltage) that occur in the configurable amplifier of Smart Analog IC 300 by using a D/A converter incorporated in Smart Analog IC 300 and an A/D converter incorporated in the microcontroller for control.

Target Device

Smart Analog IC 300 (RAA730300)

Contents

1.   Overview

1.1   General

Smart Analog IC 300 has three channels of on-chip configurable amplifiers which include a gain error and offset voltage generated by factors such as IC productive variations and ambient factors such as temperature. These errors need to be corrected when you want to amplify a very low voltage or when high-precision sensor operation is required. Smart Analog IC 300 can measure these errors by using the D/A converter in Smart Analog IC 300 and A/D converter in the microcontroller for control and correct the errors by using the microcontroller for control.

This application note mainly describes how to measure the gain error and offset voltage by using a D/A converter incorporated in Smart Analog IC 300 and an A/D converter incorporated in the microcontroller for control.

The gain error and offset voltage obtained as a result of measurement are used to calculate the voltage input to the configurable amplifier based on the voltage output from the configurable amplifier. The calculated input voltage is used as a sensing signal in which the gain error and offset voltage are corrected, enabling the creation of a system that allows more precise sensing. This correction is performed by the microcontroller for control.

For how to correct errors, see *Smart Analog IC 300   How to measure and correct errors by using MCU software (R02AN0020E).*

1.2   Related application notes

Also refer to these documents when using this application note.

- Smart Analog IC 300   Selecting Amplifiers Based on Sensor Type   Application Note (R02AN0016E)
- Smart Analog   Smart Analog Evaluating Sensors By Using Smart Analog Easy Starter (Ver. 2.0)   Application Note (R02AN0017E)
- Smart Analog IC 300/301   Features and Usage Examples (Comparison with Smart Analog IC 500 Series) Application Note (R02AN0018E)
- Smart Analog IC 300   How to measure and correct errors by using MCU software   Application Note (R02AN0020E)

2.   Factors that cause errors

This chapter describes the errors that occur in the configurable amplifier incorporated in Smart Analog IC 300 and their factors.

2.1   Gain error of the configurable amplifier

The configurable amplifiers in Smart Analog IC 300 can be configured as various amplifiers, such as inverting amplifiers, non-inverting amplifiers, and differential amplifiers. In any configuration, the gain is calculated based on the ratio of the resistance between a resistor of an input in an amplifier and a feedback resistor.

In the case of Smart Analog IC 300, this ratio of the resistance is affected by the productive variations of IC and by the fluctuation of the resistance due to the effect of ambient temperature which cannot be avoid, because the resistors which determine the gain are incorporated in Smart Analog IC 300 itself.

The gain error of Smart Analog IC 300 is defined in the specifications, however the gain error must be corrected according to the sensitivity in the system in which the sensor is applied.

2.2   Offset voltage in the configurable amplifier

In Smart Analog IC 300, offset voltage is also generated because the incorporated configurable amplifiers are operational amplifiers in a broad sense. An offset voltage is a voltage that appears at the output when the voltage difference between an inverted pin and non-inverted pin is zero.

The offset voltage is assumed to be zero in an ideal operational amplifier, but it does occur in actual operational amplifiers due to the characteristics of the input stage circuits.

The circuit of the input stage in an operational amplifier consists of an inverting input and a non-inverting input, which are implemented by a pair of transistors. The difference in electrical characteristics between these transistors is what causes the offset voltage. These differences are difficult to eliminate due to complexly interrelated factors, such as variations among semiconductor elements, that occur in the IC production process and during layout design.

The offset voltage of Smart Analog IC 300 is defined in the specifications. However, if the offset voltage can be canceled by correction, you can use the operational amplifier in a more desirable state.

3.   Procedure for measuring the error

This chapter describes how to measure the gain error and input-referred offset voltage for each amplifier configuration.

Generally, a calibrated power supply voltage or a measuring instrument is used to measure a gain error and offset voltage. This application describes how to measure and correct the gain error and offset voltage by using the features incorporated in the Smart Analog IC and microcontroller. When measuring a gain error and offset voltage, ensuring the measurement precision is an important matter. The procedure shown in this application note focuses on improving and ensuring the measurement precision.

3.1   Common items

This section describes items common to amplifier configurations and configurable amplifier channels. In this application note, to measure the voltage output from the configurable amplifier and D/A converter in Smart Analog IC 300, their pins are connected to the A/D converter input pins in the microcontroller.
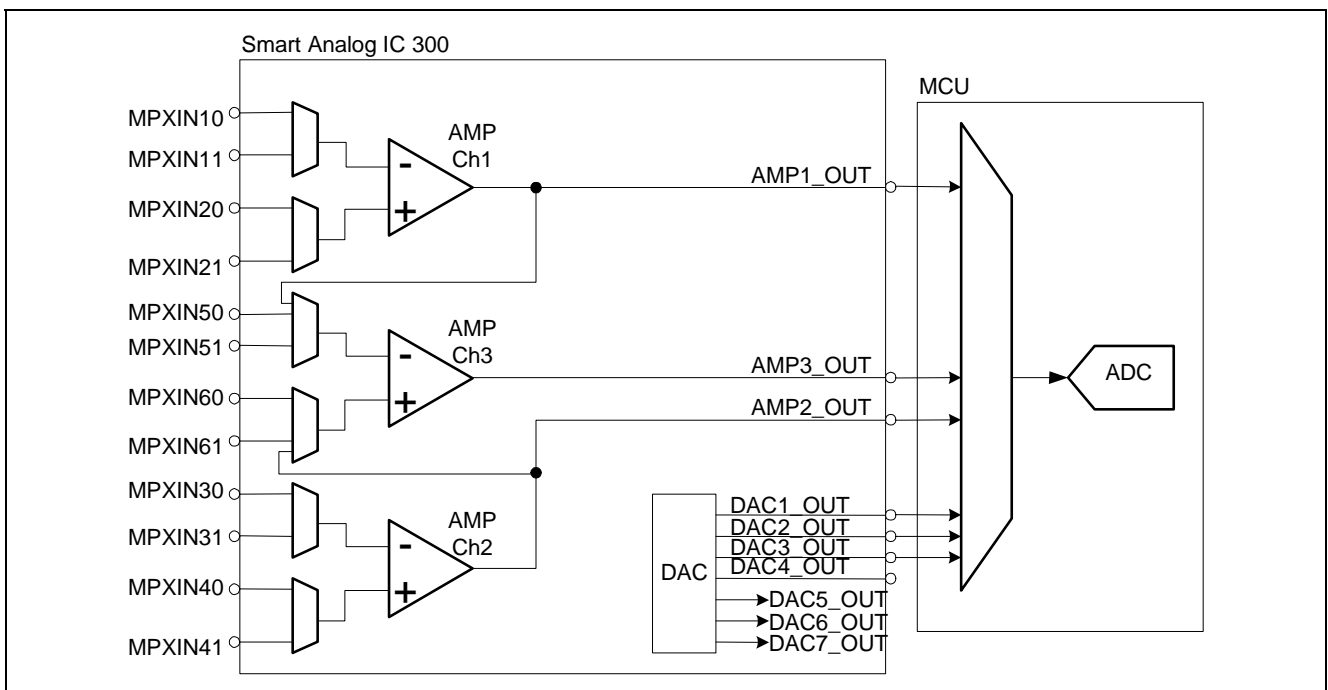

Figure 3-1   Connection diagram of Smart Analog IC 300 and microcontroller

3.2   Measurement procedure when using a differential amplifier configuration

This section describes the procedure for measuring the gain error and the input-referred offset voltage when using the configurable amplifier in the differential amplifier configuration.

3.2.1   Procedure for measuring the gain error

D/A converter is used to input the voltage to the configurable amplifier, then, the voltage output from the configurable amplifier is measured by using A/D converter. The gain is calculated by dividing the output voltage by the input voltage. In this procedure, to eliminate the offset voltage and improve the measurement precision, two measurement values are obtained by using two input voltage values. The first measurement is defined as the minimum value measurement, and the second measurement is defined as the maximum value measurement. The gain is calculated by using the difference between those two values, which is the difference of the output voltage values depending on the input voltage values. Figure 3-2 shows the gain error measurement flow.
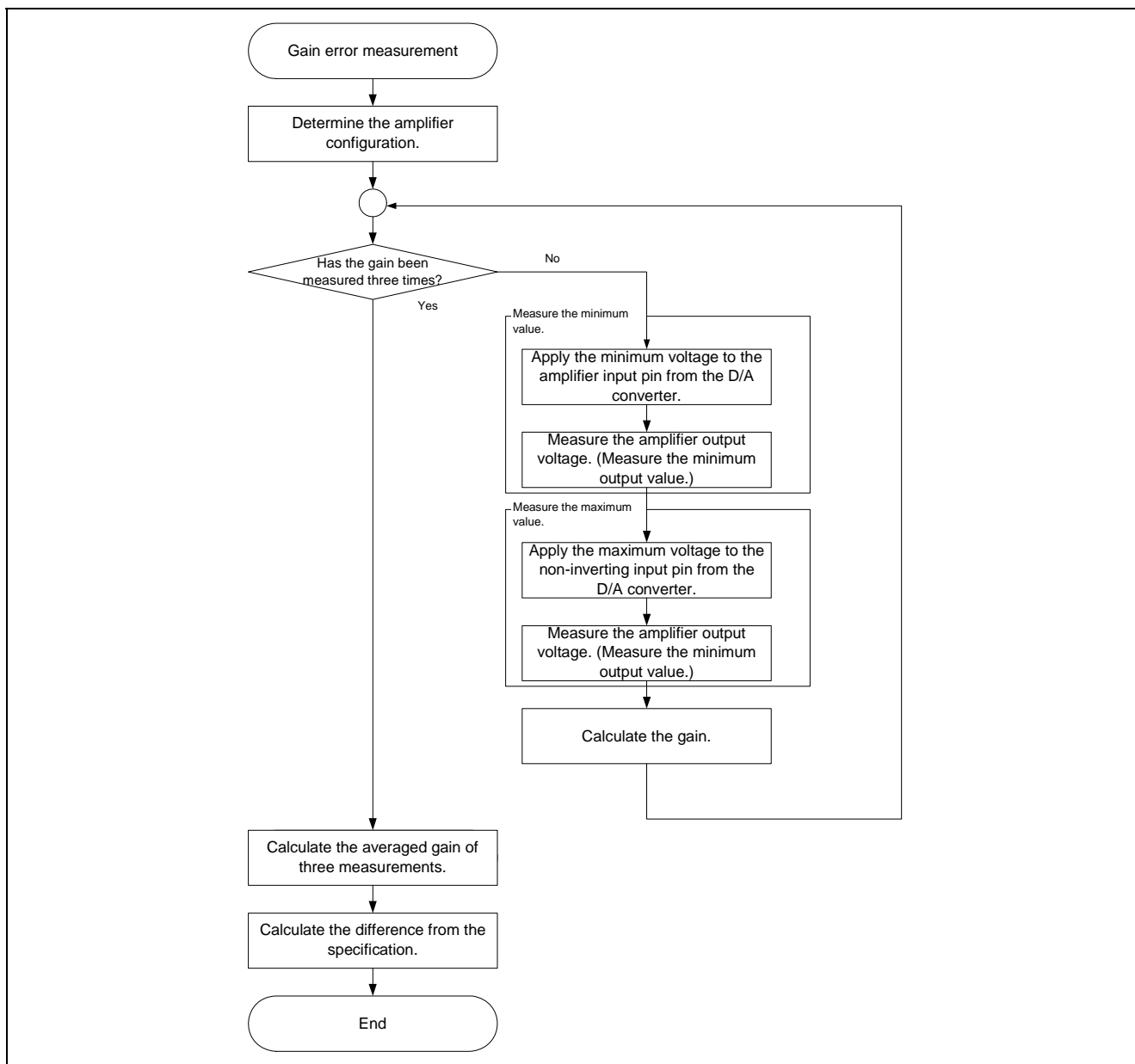

Figure 3-2   Gain error measurement flow

Smart Analog IC 300   How to measure and correct the gain error and offset voltage

(1)   **Determine the voltage input to the configurable amplifier (voltage output from the D/A converter)**

In principle, there is some errors in the D/A converters (which have 8-bit resolution) incorporated in Smart Analog IC 300. As mentioned previously, obtaining two measurement values and calculating the difference between these two values eliminates the effect of some errors except the differential linearity error. The differential linearity error can be reduced depending on how the voltage output from D/A converter is determined to be input to the configurable amplifier.

Figure 3-3 shows the differential linearity error of D/A converter Ch1 incorporated in Smart Analog IC 300. In Figure 3-3, the horizontal axis indicates the values set to the D/A converter (digital input values), and auxiliary lines are shown in 16 LSB units.
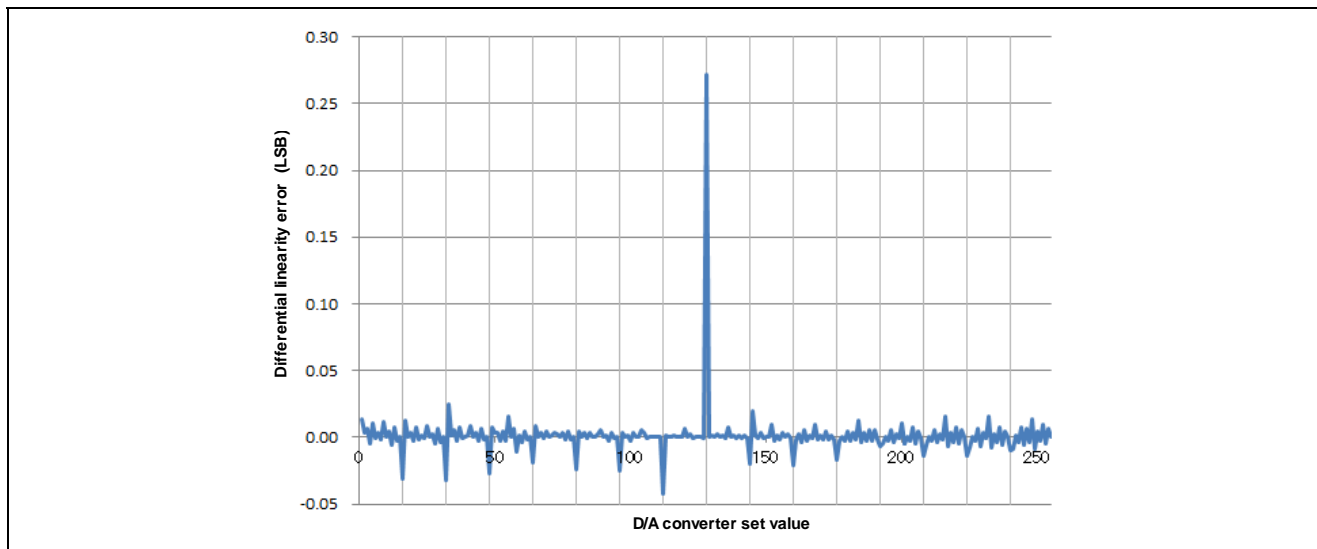

Figure 3-3   Differential linearity error of D/A converter Ch1

Note   The data shown above is measured by using a limited number of samples, and is not guaranteed. Use this data for reference only.

As shown in Figure 3-3, because the D/A converter incorporated in Smart Analog IC 300 is of the successive-approximation type, the differential linearity error increases at the point upper bits change. (For 8-bit D/A converters, the error becomes the maximum when the value changes from 127 to 128.) Therefore, it is proposed for the input voltage values to choose two setting values of D/A converter that do not extend over the point at which the error becomes maximum.

Note, however, that the measurement precision is degraded if two setting values of D/A converter is too close. When two setting values of D/A converter is too close, the difference of voltages output from D/A converter, which is the difference of voltages input to configurable amplifier, is too small. If the gain of configurable amplifier is low, the difference of voltages output from configurable amplifier, which is the difference of voltages input to A/D converter, becomes narrow and the measurement precision is degraded because that quantization error could be dominant.

For the above reasons, you need to consider the configurable amplifier gain and precision of the A/D converter in the microcontroller for control when determining the D/A converter output voltage to be input to the configurable amplifier.

In this application note, two setting values of D/A converter which determine output voltages are selected within the range of 16LSB. As the first selection, set x0H (x = 0 to F) for the setting value (digital input value) of D/A converter. This is called *minimum value measurement*. As the second selection, add 16 or less to the setting value (digital input value) which is used on minimum value measurement. This is called *maximum value measurement*.

When using the configurable amplifier as a differential amplifier, three D/A converter channels are used. On minimum value measurement, set x0H (x = 0 to F) for the setting value (digital input value) of all three D/A converter channels. On maximum value measurement, add 16 or less to the setting value (digital input value) which is used on minimum value measurement, however only of the D/A converter connected with non-inverting input of the configurable amplifier.

(2)   **Minimum value measurement**

Three D/A converter channels are connected respectively with the inverting input and the non-inverting input to supply the input voltage and reference voltage. All three setting values of D/A converter which determine the voltages output from D/A converter (V_{IN_min}) are specified to be the same. The measured result under this condition (the voltages output from configurable amplifier) is called the minimum value voltage ($V_{AMP\_OUT\_min}$).
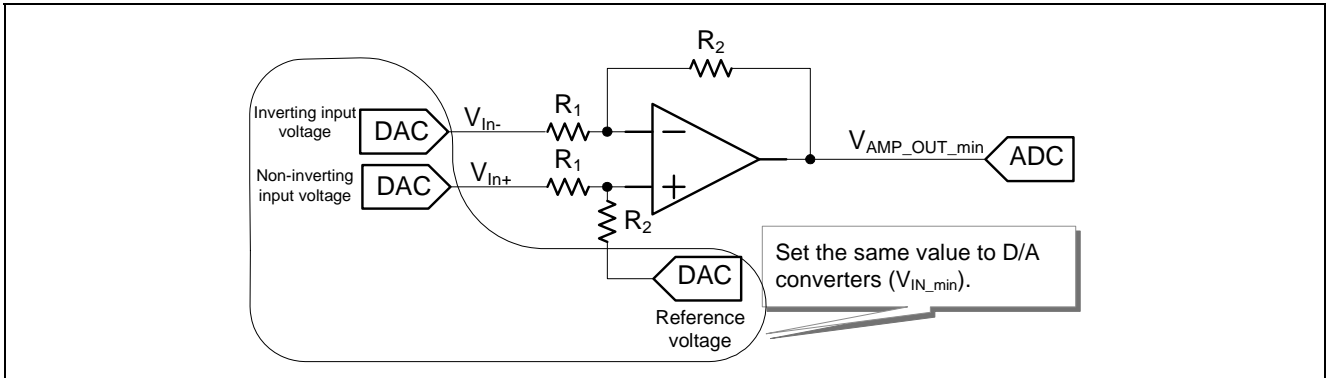

Figure 3-4   Minimum value measurement

(3)   **Maximum value measurement**

Next, change the setting value (digital input value) which should be grater than the one used on minimum value measurement, only of the D/A converter connected with non-inverting input of the configurable amplifier. Select the setting values referring to Table 3-1. Do not change the setting values which determined the voltage input to inverting input and the reference voltage input to non-inverting input. The voltage supplied to non-inverting input is expressed as V_{IN}_max, and the measured result under this condition (the voltages output from configurable amplifier) is called the maximum value voltage ($V_{AMP\_OUT}\_max$).
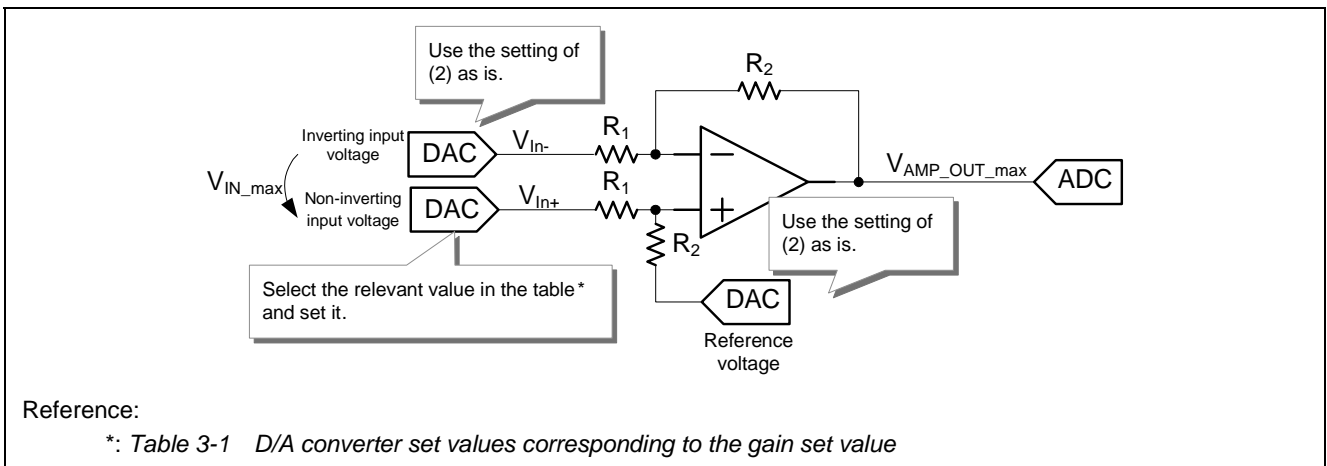

Reference:
    *: *Table 3-1   D/A converter set values corresponding to the gain set value*

Figure 3-5   Maximum value measurement

Table 3-1   D/A converter set values corresponding to the gain set value

Number of averaging times	Reference voltage on inverting input	Input voltage on non-inverting input (per gain set value)									
		0-7 (6-20dB)	8 (22dB)	9 (24dB)	10 (26dB)	11 (28dB)	12 (30dB)	13 (32dB)	14 (34dB)	15 (36dB)	16, 17 (38,40dB)
1st	20H	2FH	2DH	2AH	28H	26H	25H	24H	23H	22H	21H
2nd	30H	3FH	3DH	3AH	38H	36H	35H	34H	33H	32H	31H
3rd	40H	4FH	4DH	4AH	48H	46H	45H	44H	43H	42H	41H

Note   For the maximum value measurement, the value set to the non-inverting input is prescribed so that the difference from the inverting input voltage becomes the maximum, within the allowable A/D converter input range.

The value is measured three times and the results are averaged

(4) **Calculating the gain**

The gain are calculated using the minimum and maximum value voltages, and the voltage supplied to non-inverting input (the voltage output from D/A converter). Generally, a gain is obtained by dividing the output voltage by the input voltage. However, the gain obtained by using division includes the offset voltage. In this application note, relative values are used to calculate the gain that does not include the offset voltage. Gain G is expressed as shown in Formula 1 below.

$$G = \frac{V_{AMP\_OUT\_max} - V_{AMP\_OUT\_min}}{V_{IN\_max} - V_{IN\_min}}$$ ...   Formula 1

(5) **Averaging the results**

To improve the measurement precision, change the voltage level supplied from the D/A converters and repeat steps (1) to (4) to measure the value multiple times (three times in the examples shown in this application note). After measurement is performed three times, the gain is calculated to average the obtained data.

(6) **Calculating the gain error**

The gain error is calculated using the difference between the measured value averaged in (5) and the value prescribed in the specifications. For details, see *4.1.1 Calculating the gain error*.

3.2.2   Procedure for measuring the input-referred offset voltage

Input the same voltage to the inverted input pin and the non-inverted input pin in the configurable amplifier, and measure the voltage output from the configurable amplifier. Calculate the offset voltage by measuring the difference between the input voltage and output voltage. The input-referred offset voltage is obtained by dividing the offset voltage by the amplifier gain. Figure 3-6 shows the input-referred offset voltage measurement flow.
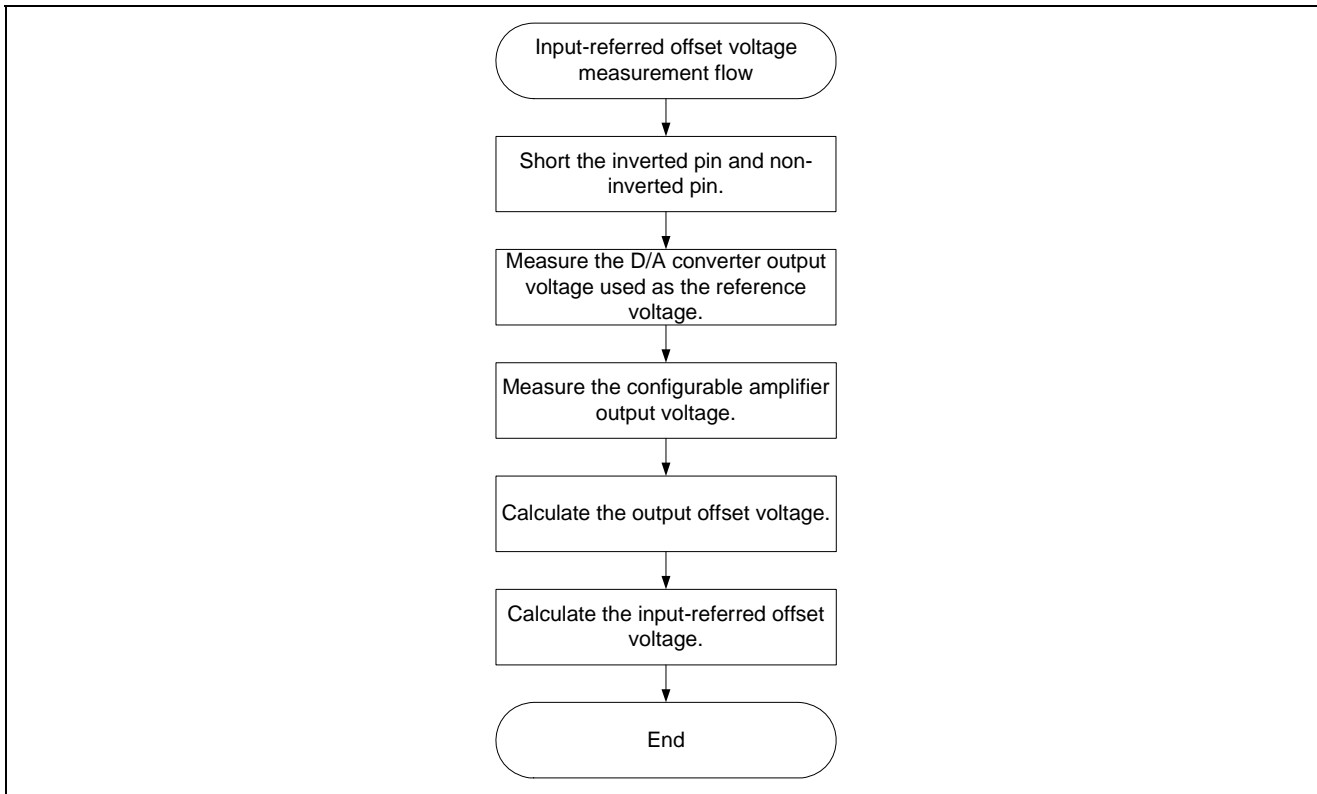

Figure 3-6   Input-referred offset voltage measurement flow

The procedure is described below in detail based on the flow shown in Figure 3-6.

(1)   **Shorting the inverted pin and non-inverted pin**

Figure 3-7 shows the block diagram of an offset voltage measurement system in a differential amplifier configuration. Short the inverted pin and non-inverted pin as shown in Figure 3-7 to make the voltage input to the configurable amplifier the same.
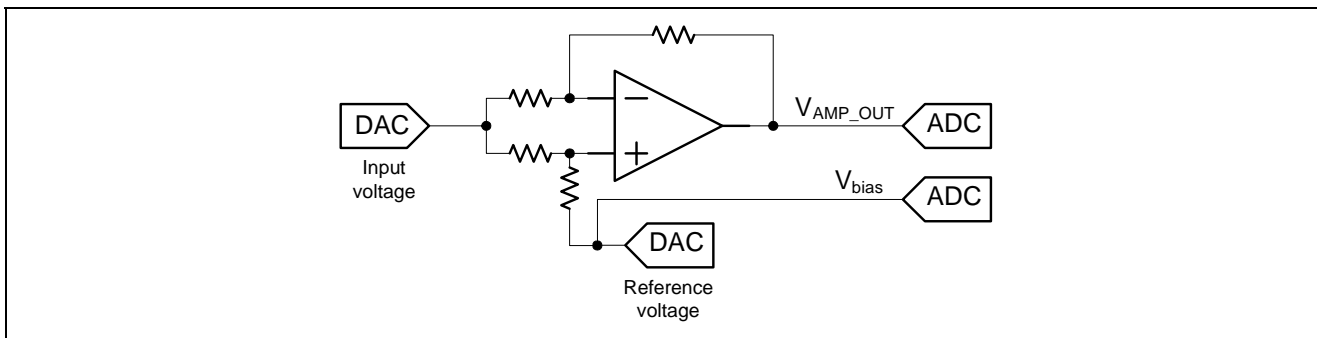

Figure 3-7   Measuring the offset voltage when using a differential amplifier configuration

(2)   **Measuring the D/A converter output voltage**

The voltage output from D/A converter that is used as the reference voltage for the configurable amplifier is measured. In Figure 3-7, two D/A converter channels are used, however the voltage form one of them is not required to be measured because the voltage output from the D/A converter that supplies the input voltage is just offset as a differential signal. Therefore, measure only the voltage output from the D/A converter that supplies the reference voltage by using an A/D converter.

Here, for the voltage output from the two D/A converter channels, specify a value that is the same or nearly the same value as the input voltage and reference voltage of the configurable amplifier used in the actual system. Due to the operational amplifier characteristics, the offset voltage might depend on the input voltage or reference value.

Note   Use an A/D converter that has a resolution higher than that of the D/A converter (8 bits) for measurement.

(3)   **Measuring the configurable amplifier output voltage**

After supplying the input voltage and the reference voltage to the configurable amplifier, the voltage output from the configurable amplifier is measured by using the A/D converter. Here, the gain of the differential amplifier is specified to be the value used in the actual system.

(4)   **Calculating the offset voltage**

Calculate the offset voltage based on the voltage value measured by using the A/D converter.

Based on the non-inverting input pin voltage (V_{IN+}), inverting input pin voltage (V_{IN-}), reference voltage (V_{bias}), and the differential amplifier gain (G_{diff}), the output voltage (V_{AMP_OUT}) in the differential amplifier configuration is expressed by using Formula 2.

$$V_{AMP\_OUT} = \left(V_{IN+} - V_{IN-}\right) \cdot G_{diff} + V_{bias}$$

...   Formula 2

Formula 2 indicates the perfect amplifier that does not cause the offset voltage. However, the voltage output from an actual amplifier generally includes the offset voltage. Formula 2 is transformed to Formula 3, where V_{offset_output} is offset voltage.

$$V_{AMP\_OUT} = \left(V_{IN+} - V_{IN-}\right) \cdot G_{diff} + V_{bias} + V_{offset\_output}$$

...   Formula 3

Because the same potential is supplied to the non-inverting input pin voltage (V_{IN+}) and inverting input pin voltage (V_{IN-}), terms V_{IN+} and V_{IN-} are offset from Formula 3, which results in Formula 4.

$$V_{offset\_output} = V_{AMP\_OUT} - V_{bias}$$

...   Formula 4

By substituting the measured value to V_{bias} and V_{AMP_OUT} in Formula 4, the offset voltage can be obtained.

(5)   **Calculating the input-referred offset voltage**

Calculate the input-referred offset voltage (V_{offset_input}) based on the offset voltage (V_{offset_output}). The input-referred offset voltage is obtained by dividing the offset voltage by the gain. It is expressed by using Formula 5.

$$V_{offset\_input} = \frac{V_{offset\_output}}{G_{diff}}$$

...   Formula 5

3.2.3   Measuring the gain error by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the gain error, based on the descriptions in *3.2.1*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Minimum value measurement**

Figure 3-8 to Figure 3-10 show how a circuit is configured for minimum value measurement and the circuit setting conditions.
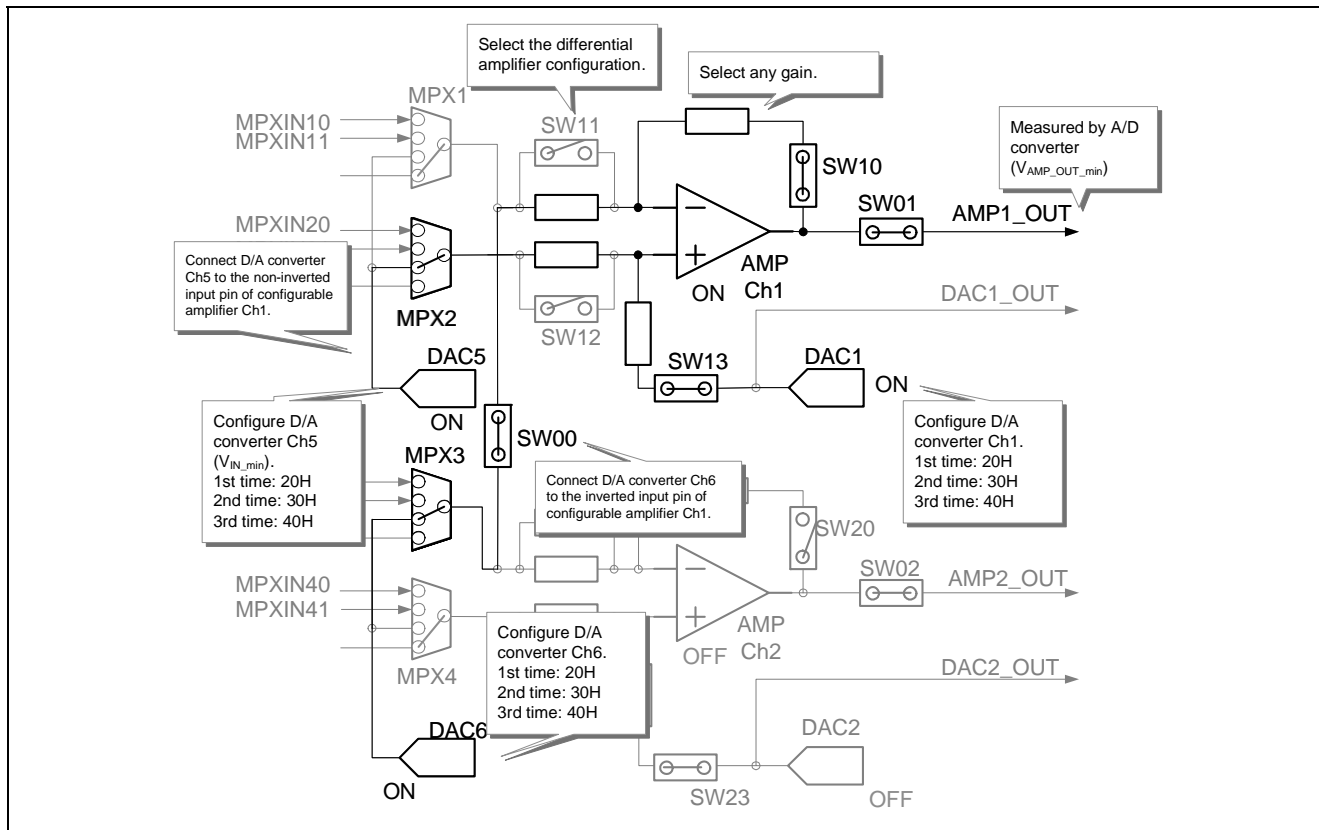

Figure 3-8   Configurable amplifier Ch1 for minimum value measurement
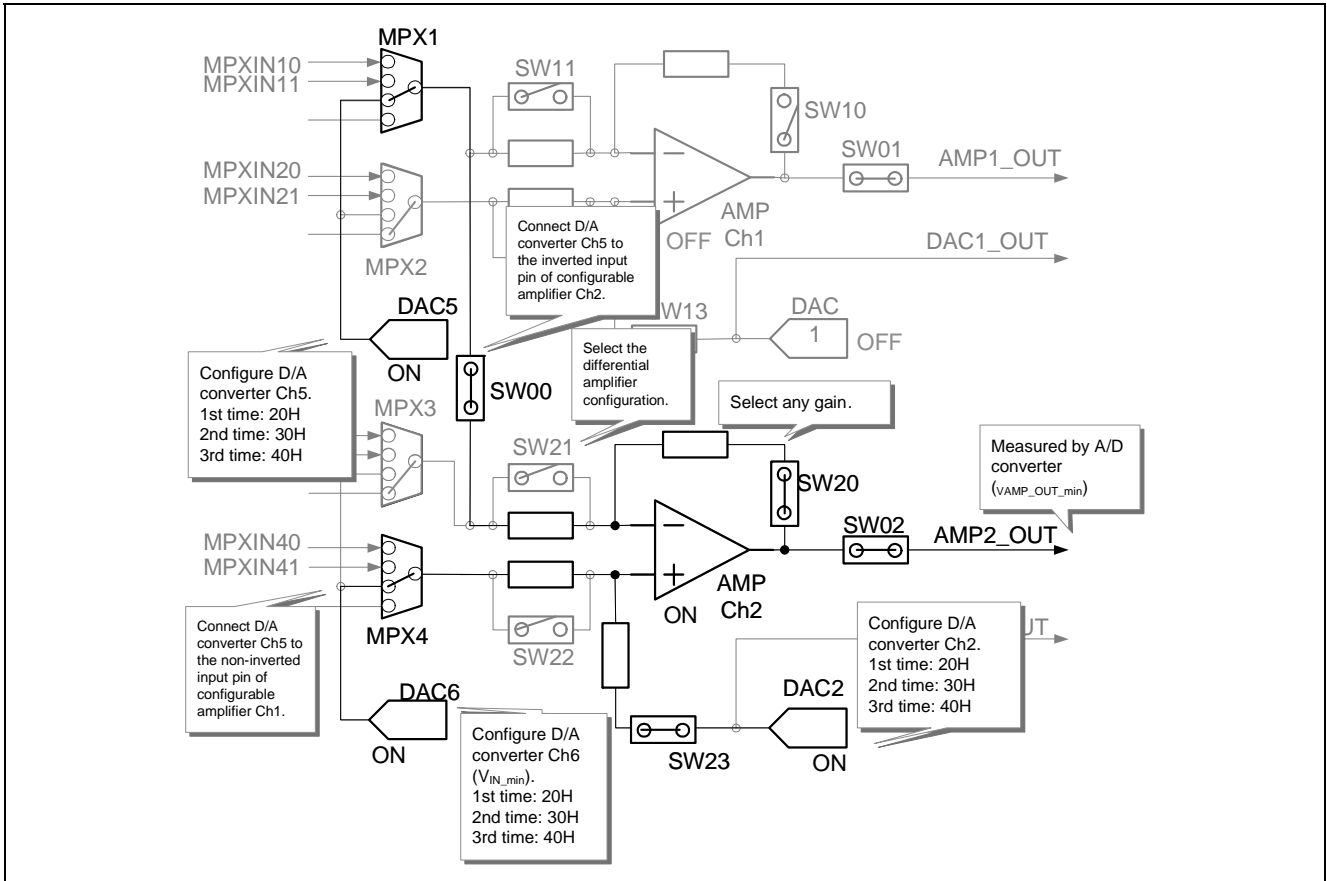
Figure 3-9   Configurable amplifier Ch2 for minimum value measurement
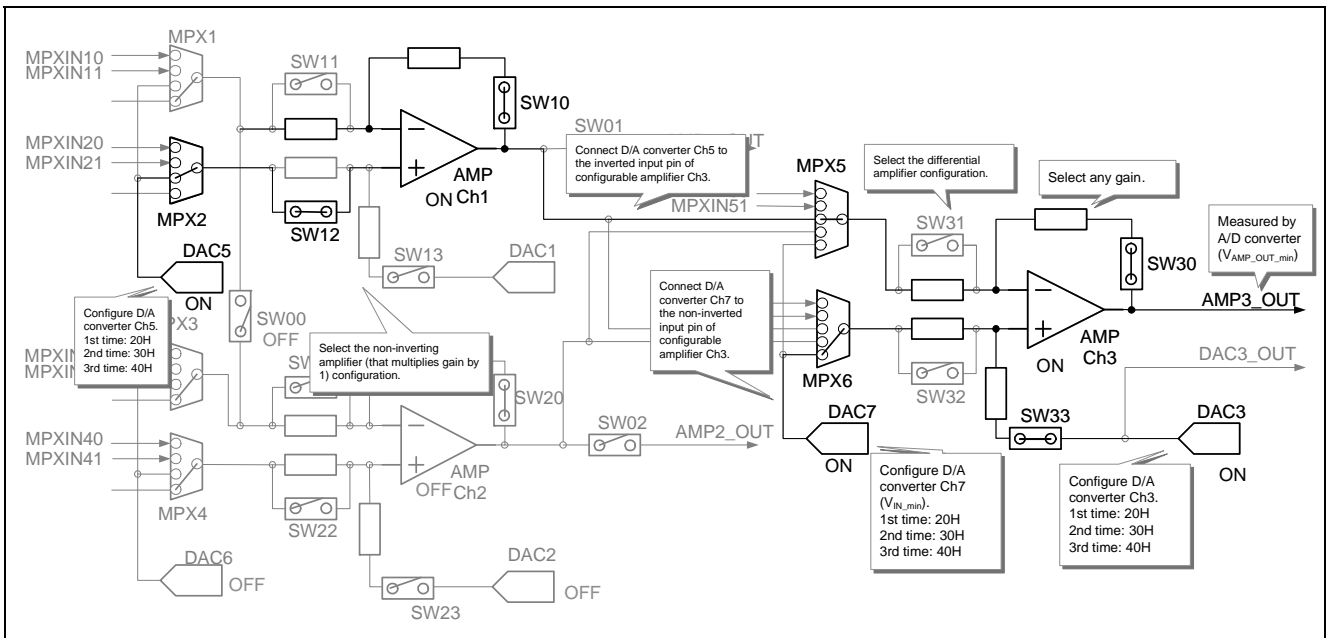
Figure 3-10   Configurable amplifier Ch3 for minimum value measurement

(2)   **Maximum value measurement**

Figures 3-11 to 3-13 show how a circuit is configured for maximum value measurement and the circuit setting conditions. Do not change the input voltage on the inverting input and the reference voltage on the non-inverting input set in *(1) Maximum value measurement*.
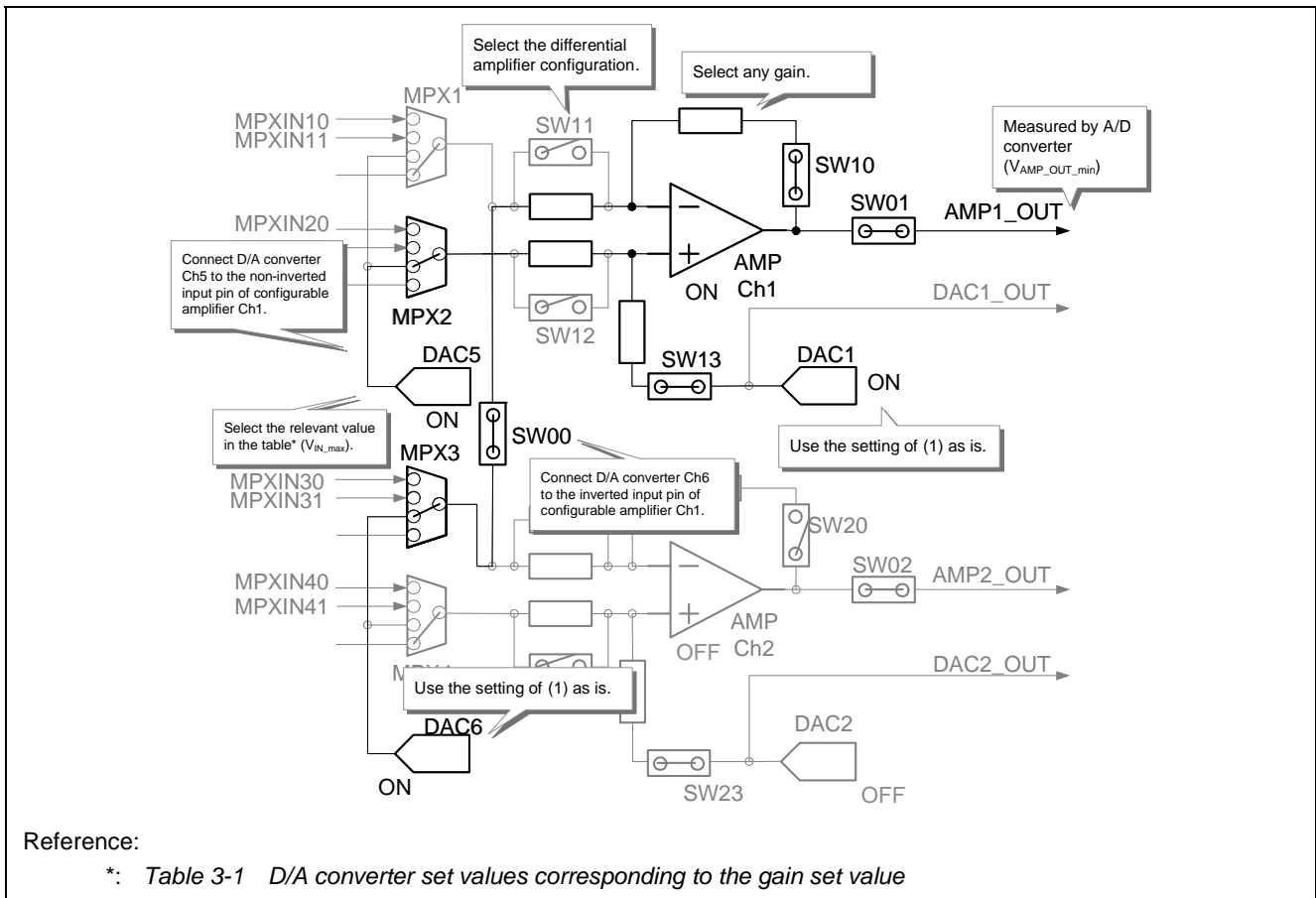
Figure 3-11   Configurable amplifier Ch1 for maximum value measurement

Reference:
*:   *Table 3-1   D/A converter set values corresponding to the gain set value*
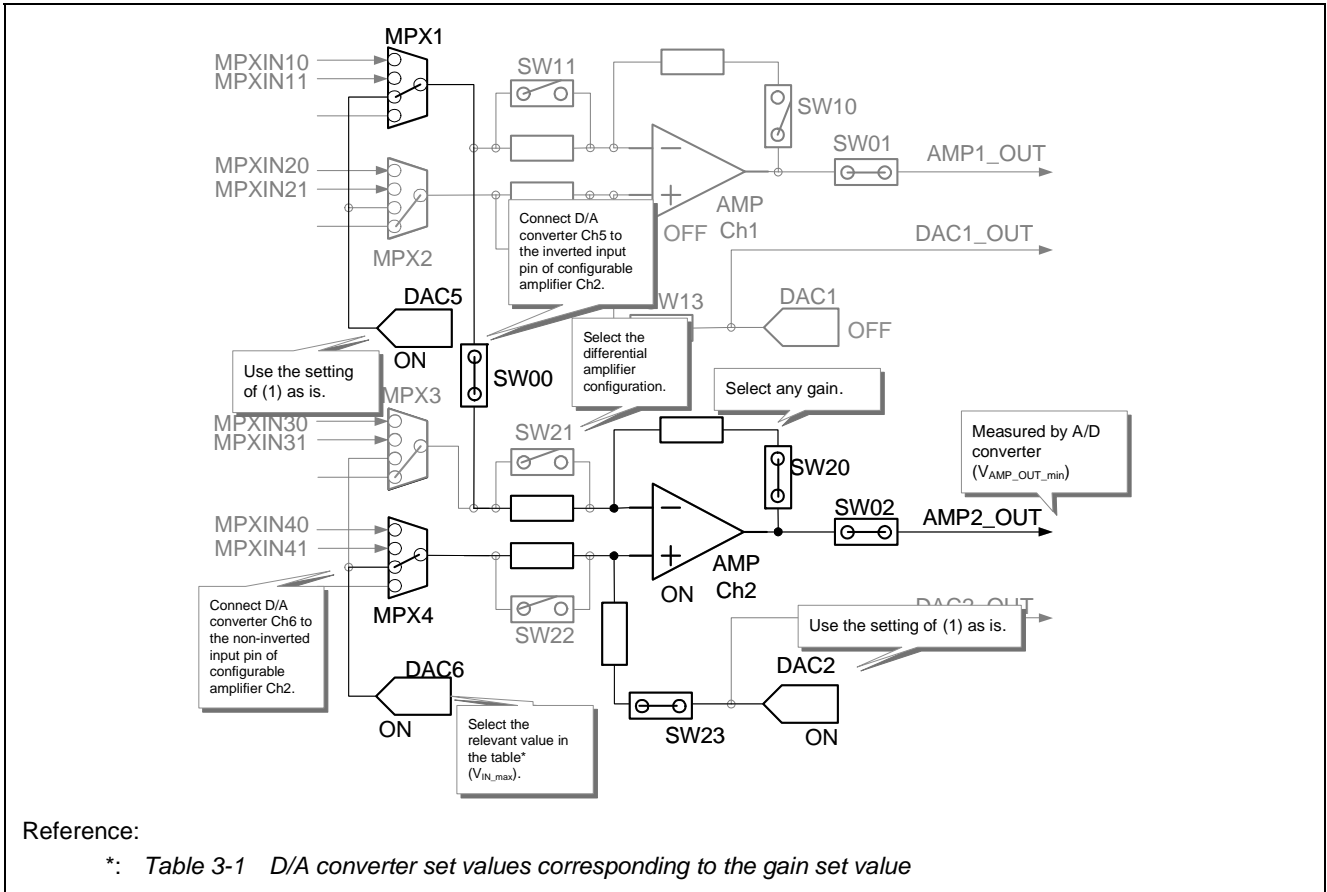
Figure 3-12   Configurable amplifier Ch2 for maximum value measurement

Reference:
*:   *Table 3-1   D/A converter set values corresponding to the gain set value*

Figure 3-13   Configurable amplifier Ch3 for maximum value measurement

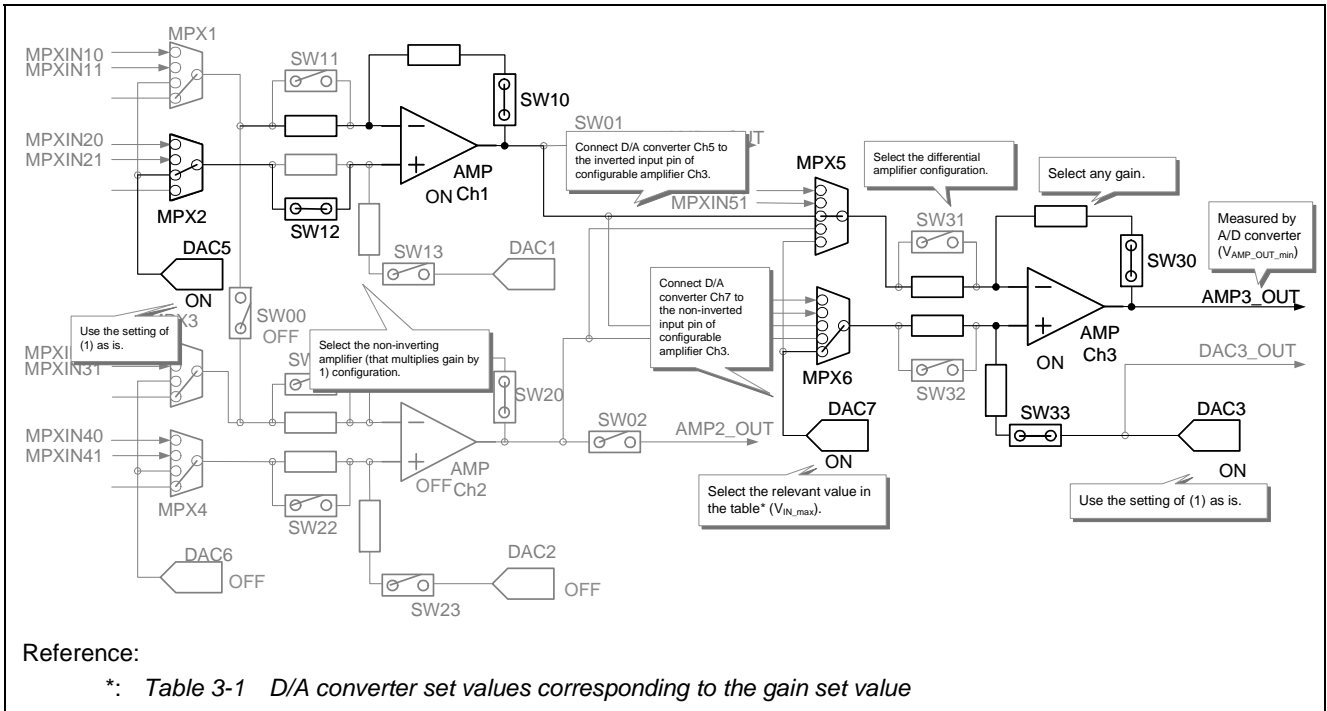(3)   **Calculating the gain**

Calculate the configurable amplifier output voltage (V_{AMP_OUT}) based on the value measured by using the A/D converter (A/D-converted value). Based on the value measured by using the A/D converter (N_{AMP_OUT}) and power supply voltage (AV_{DD}), calculate the gain by using Formula 6.

$$V_{AMP\_OUT} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD}$$ ...   Formula 6

Note n indicates the resolution of the A/D converter.

The minimum value voltage ($V_{AMP\_OUT\_min}$) and maximum value voltage ($V_{AMP\_OUT\_max}$) can be calculated by using Formula 6.

The input voltage (V_{IN}) is expressed by using Formula 7, based on the D/A converter set value (N_{DAC}), upper limit of the reference voltage (V_{VRT}), and lower limit of the reference voltage (V_{VRB}).

$$V_{IN} = \left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \frac{N_{DAC}}{2^8} \right) + 2 \cdot V_{VRB}$$ ...   Formula 7

Note 8 indicates the number of bits as the unit of resolution.

Thus, gain G is expressed by using Formula 8, based on Formula 1, Formula 6, and Formula 7.

$$G = \frac{\left(N_{AMP\_OUT\_Max} - N_{AMP\_OUT\_Min} \right) \cdot \dfrac{AV_{DD}}{2^n}}{\left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \dfrac{\left(N_{IN\_Max} - N_{IN\_Min} \right)}{2^8} \right) + 2 \cdot V_{VRB}}$$ ...   Formula 8

(4)   **Averaging the results**

If the results of measurement to be averaged (measurement is performed three times in this application note) are G_{First}, G_{Second}, and G_{Third} respectively, the average $G_{Average}$ is expressed by using Formula 9.

$$G_{Average} = \frac{G_{First} + G_{Second} + G_{Third}}{3}$$ ...   Formula 9

(5)   **Calculating the gain error**

Calculate the difference from the value prescribed in the specifications, and then calculate the gain based on the value measured and averaged in (4). For details, see *4.1.1 Calculating the gain error*.

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3.2.4   Measuring the input-referred offset voltage by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the input-referred offset voltage, based on the descriptions in *3.2.2*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Measuring the D/A converter (with an external pin) output voltage**

Figure 3-14 to Figure 3-16 show examples of measuring the voltage output from D/A converters incorporated in Smart Analog IC 300.
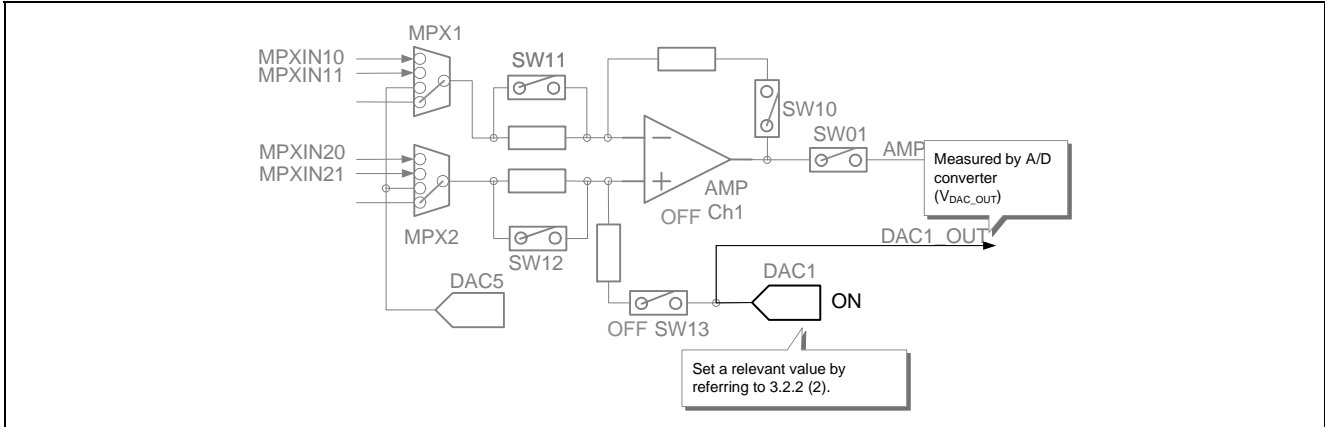

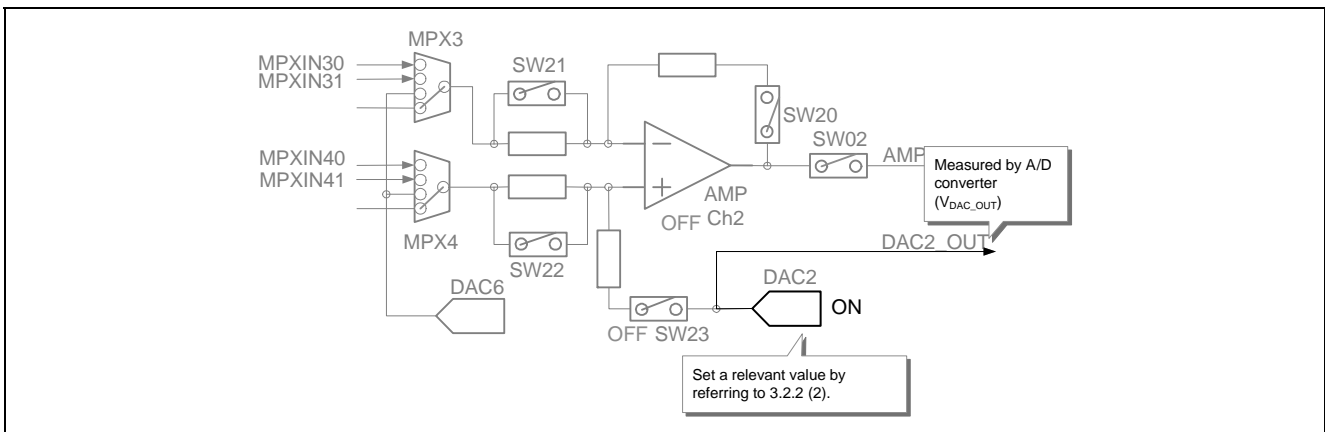**Figure 3-14   D/A converter Ch1 for output voltage measurement**

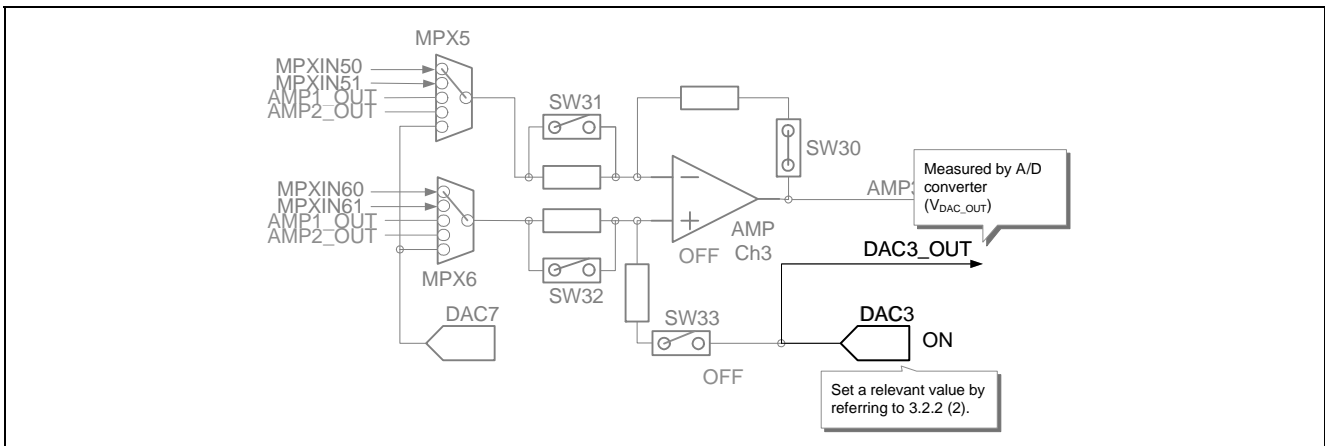**Figure 3-15   D/A converter Ch2 for output voltage measurement**

Figure 3-16   D/A converter Ch3 for output voltage measurement

Based on the value measured by using the A/D converter (A/D-converted value) (N_{DAC_OUT}) and power supply voltage (AV_{DD}), calculate the D/A converter output voltage (V_{DAC_OUT}) by using Formula 10.

$$V_{DAC\_OUT} = \frac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD}$$ ...   Formula 10

Note   n indicates the resolution of the A/D converter.

(2)   **Measuring the configurable amplifier output voltage**

Input the same voltage to the inverted input pin and the non-inverted input pin in the configurable amplifier, and measure the voltage output from the configurable amplifier.

Figure 3-17 to Figure 3-19 show examples of measuring the voltage output from the configurable amplifier incorporated in Smart Analog IC 300.
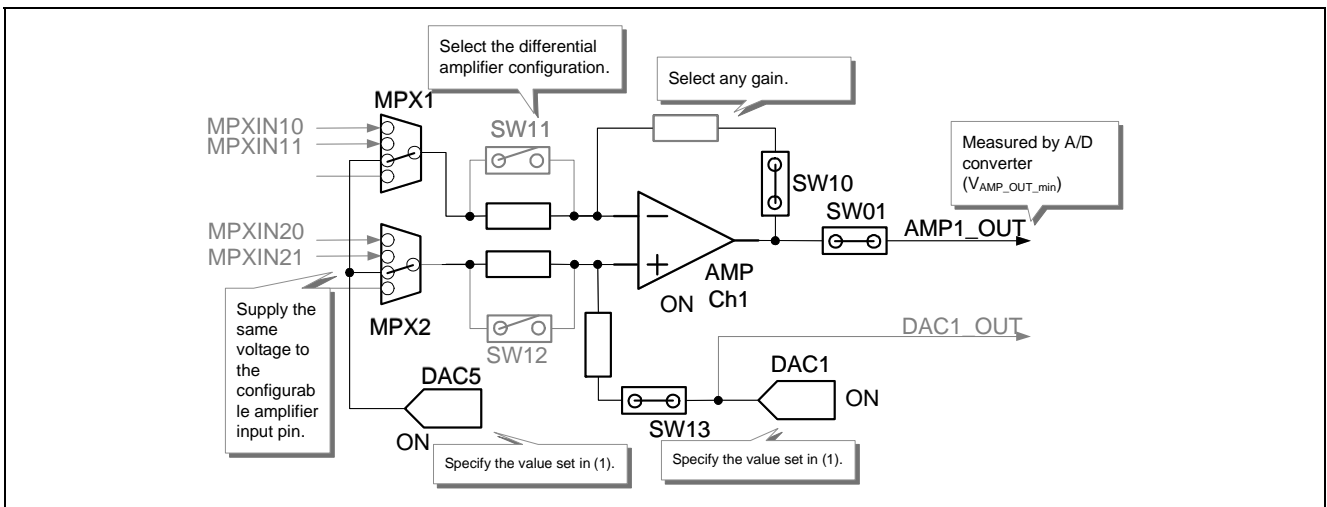

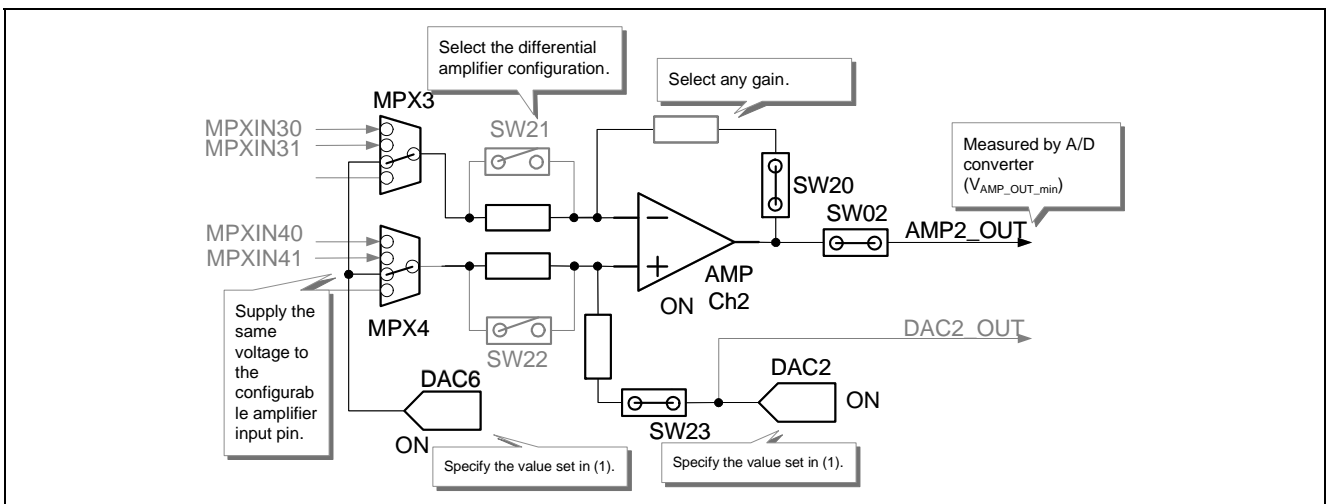**Figure 3-17   Configurable amplifier Ch1 for output voltage measurement**

Figure 3-18   Configurable amplifier Ch2 for output voltage measurement
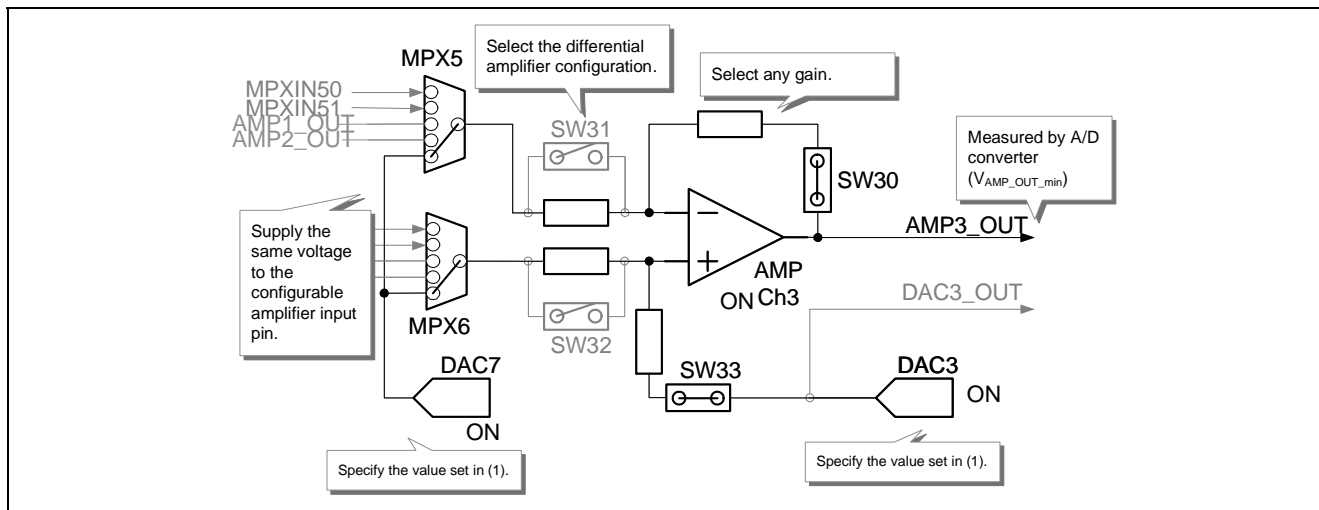
Figure 3-19   Configurable amplifier Ch3 for output voltage measurement

Based on the value measured by using the A/D converter (A/D-converted value), calculate the configurable amplifier output voltage (V_{AMP_OUT}) by using Formula 6.

$$V_{AMP\_OUT} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} \qquad ... \qquad \text{Formula 6}$$

Note   n indicates the resolution of the A/D converter.

(3)   **Calculating the offset voltage**

Calculate the offset voltage by substituting the values obtained in *(1) Measuring the D/A converter (with an external pin) output voltage* and *(2) Measuring the configurable amplifier output voltage* to Formula 4. Sustituting Formula 6 and Formula 10 in Formula 4 results in Formula 11.

$$V_{offset\_output} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} - \frac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD} \qquad ... \qquad \text{Formula 11}$$

(4)   **Calculating the input-referred offset voltage**

Calculate the input-referred offset voltage based on the offset voltage. The input-referred offset voltage can be calculated by using Formula 5 and Formula 11, which results in Formula 12. G_{diff} is the gain that has been used for measurement.

$$V_{Offset} = \frac{\dfrac{ADC_{AMP\_OUT}}{2^n - 1} \cdot AV_{DD} - \dfrac{ADC_{DAC\_OUT}}{2^n - 1} \cdot AV_{DD}}{G_{diff}} \qquad ... \qquad \text{Formula 12}$$

3.3   Measurement procedure when using an inverting or non-inverting amplifier configuration

This section describes the procedure for measuring the gain error and the input-referred offset voltage when using the configurable amplifier in the inverting or non-inverting amplifier configuration. The inverting or non-inverting amplifier configuration only differ in the D/A converter output voltage to be input to the configurable amplifier, and the other settings are the same.

3.3.1   Procedure for measuring the gain error

The procedure for measuring the gain error is the same as that used in the differential amplifier configuration (see *3.2.1*). For details about the measurement flow and its description, see *3.2.1*.

(1)   **Determine the voltage input to the configurable amplifier (voltage output from the D/A converter)**

Based on the concept described in *3.2.1 (1)*, determine the voltage input to the configurable amplifier (the voltage output from the D/A converter).

When using the configurable amplifier as an inverting or non-inverting amplifier, use two D/A converter channels. As the digital input value, set the D/A converters to xFH (x = 2 to 4) in the inverting amplifier configuration, or x0H (x = 2 to 4) in the inverting amplifier configuration, for minimum value measurement. For minimum value measurement, set the D/A converters by referring to Table 3-2 or Table 3-3.

(2)   **Minimum value measurement**

Connect separate D/A converter channels to supply the input voltage on the inverting input, and the input voltage on the non-inverting input. Specify the same voltage to be output from all the D/A converter channels (V_{IN_min}). Use the result measured under these conditions (configurable amplifier output voltage) as the minimum value voltage ($V_{AMP\_OUT\_min}$). The value to be set as V_{IN_min} differs between the inverting amplifier configuration and the non-inverting amplifier configuration. For details, see Table 3-2 or Table 3-3.

Figure 3-20   Minimum value measurement

(3)   **Maximum value measurement**

Change the D/A converter set value to generate a differential voltage between the inverting input and non-inverting input. Here, the D/A converter whose setting is to be changed differs between the inverting amplifier configuration and the non-inverting amplifier configuration. For the value to be set, see Table 3-2 or Table 3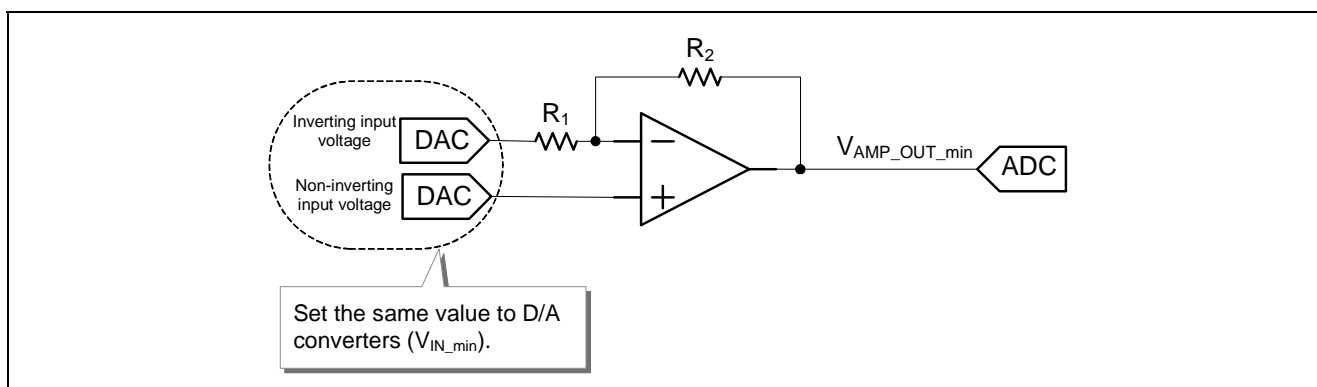-3. Here, the voltage supplied to the inverting or non-inverting input is expressed as V_{IN_max}, and the configurable amplifier output voltage obtained as a result of measurement is expressed as the maximum value voltage ($V_{AMP\_OUT\_max}$).
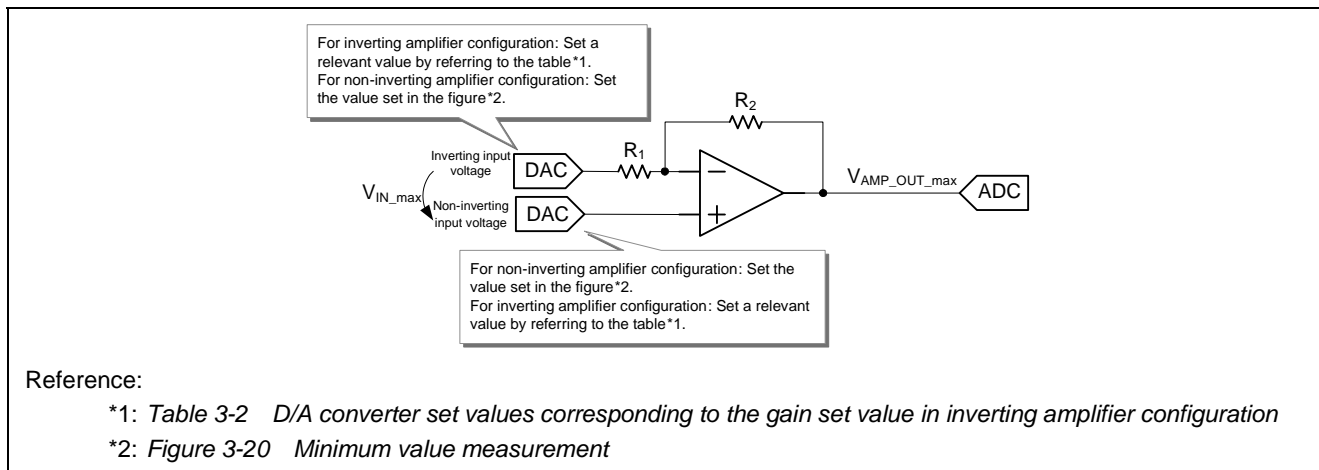
Reference:
*1: *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration*
*2: *Figure 3-20   Minimum value measurement*

Figure 3-21   Maximum value measurement

Table 3-2 D/A converter set values corresponding to the gain set value in inverting amplifier configuration

Number of averaging times	Non-inverting input	Inverting input (per gain set value)									
		0-7 (6-20dB)	8 (22dB)	9 (24dB)	10 (26dB)	11 (28dB)	12 (30dB)	13 (32dB)	14 (34dB)	15 (36dB)	16, 17 (38,40dB)
1st	2FH	20H	22H	25H	27H	29H	2AH	2BH	2CH	2DH	2EH
2nd	3FH	30H	32H	35H	37H	39H	3AH	3BH	3CH	3DH	3EH
3rd	4FH	40H	42H	45H	47H	49H	4AH	4BH	4CH	4DH	4EH

Note   For the maximum value measurement, the value set to the inverting input is prescribed so that the difference from the non-inverting input voltage becomes the maximum, within the allowable A/D converter input range.
The value is measured three times and the results are averaged.

Table 3-3 D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration

Number of averaging times	Inverting input	Non-inverting input (per gain set value)									
		0-7 (9.5-20.8dB)	8 (22.7dB)	9 (24.5dB)	10 (26.4dB)	11 (28.3dB)	12 (30.3dB)	13 (32.2dB)	14 (34.2dB)	15 (36.1dB)	16, 17 (38.1, 40.1dB)
1st	20H	2FH	2DH	2AH	28H	26H	25H	24H	23H	22H	21H
2nd	30H	3FH	3DH	3AH	38H	36H	35H	34H	33H	32H	31H
3rd	40H	4FH	4DH	4AH	48H	46H	45H	44H	43H	42H	41H

Note   For the maximum value measurement, the value set to the non-inverting input is prescribed so that the difference from the inverting input voltage becomes the maximum, within the allowable A/D converter input range.
The value is measured three times and the results are averaged.

(4) **Calculating the gain**

Calculate the gain based on the minimum and maximum value voltages and the voltage supplied to the inverting or non-inverting input (D/A converter output voltage). Generally, a gain is obtained by dividing the output voltage by the input voltage. However, the gain obtained by using division includes the offset voltage. In this application note, relative values are used to calculate the gain that does not include the offset voltage. Gain G is expressed as shown in Formula 1 below.

$$G = \frac{V_{AMP\_OUT\_max} - V_{AMP\_OUT\_min}}{V_{IN\_max} - V_{IN\_min}}$$ ...   Formula 1

(5)   **Averaging the results**

To improve the measurement precision, change the voltage level supplied from the D/A converters and repeat steps (1) to (4) to measure the value multiple times (three times in the examples shown in this application note). After measurement is performed three times, average the obtained data to obtain the gain.

(6)   **Calculating the gain error**

Calculate the difference from the value prescribed in the specifications, and then calculate the gain based on the value measured and averaged in (5). For details, see *4.1.1 Calculating the gain error*.

3.3.2   Procedure for measuring the input-referred offset voltage

Input the same voltage to the inverted input pin and the non-inverted input pin in the configurable amplifier, and measure the voltage output from the configurable amplifier. Calculate the offset voltage by measuring the difference between the input voltage and output voltage. The input-referred offset voltage is obtained by dividing the offset voltage by the amplifier gain. Figure 3-22 shows the input-referred offset voltage measurement flow.
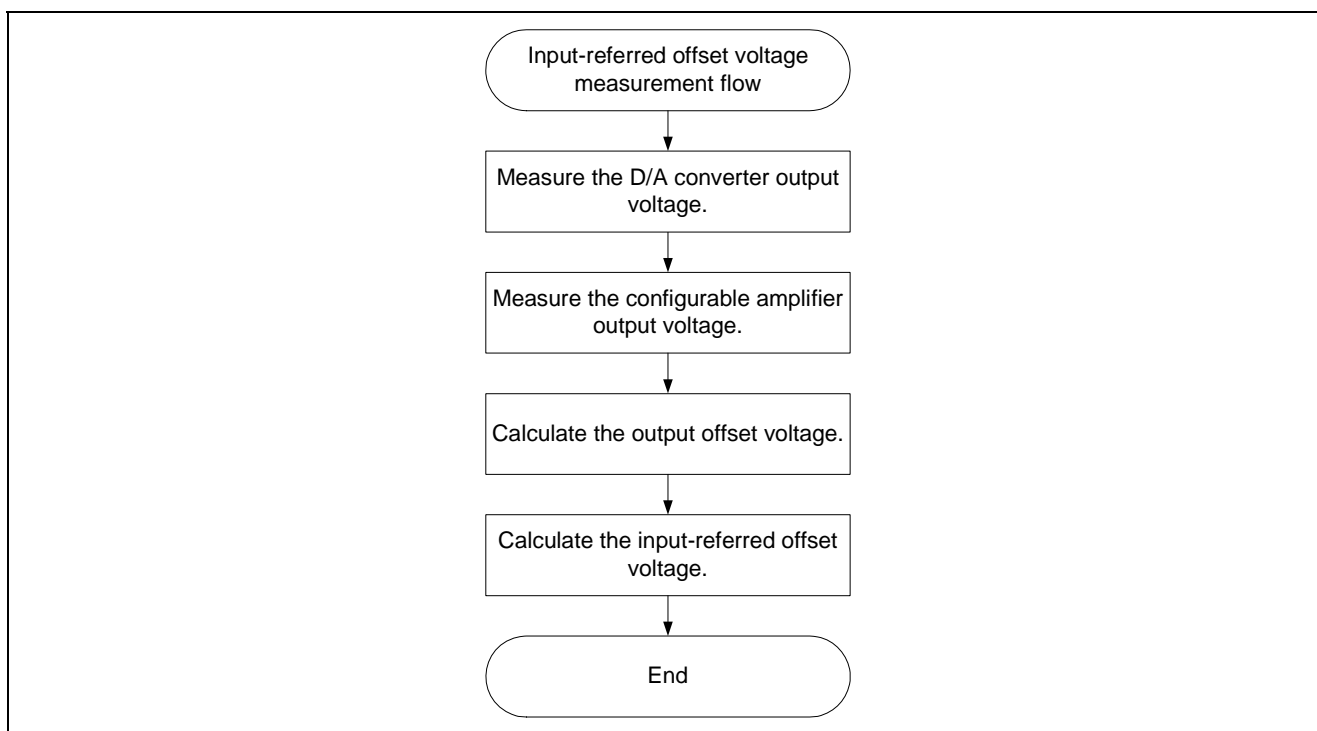

Figure 3-22   Input-referred offset voltage measurement flow

The procedure is described below in detail based on the flow shown in Figure 3-22.

(1)   **Measuring the D/A converter output voltage**

Measure the D/A converter output voltage that is used as the reference voltage for the configurable amplifier. Figure 3-23 shows the block diagram for measurement. The D/A converter used here does not have an external output pin, so measure the D/A converter output voltage by using the A/D converter via a feedback resistor connected to the configurable amplifier, as shown in Figure 3-23. Specify the resistance of the feedback resistor as low as possible.

Here, for the voltage output from the D/A converters, specify the same or near value as the input voltage of the configurable amplifier used in the actual system. Due to the operational amplifier characteristics, the offset voltage might depend on the input voltage or reference value.

Note Use an A/D converter that has a resolution higher than that of the D/A converter (8 bits) for measurement.
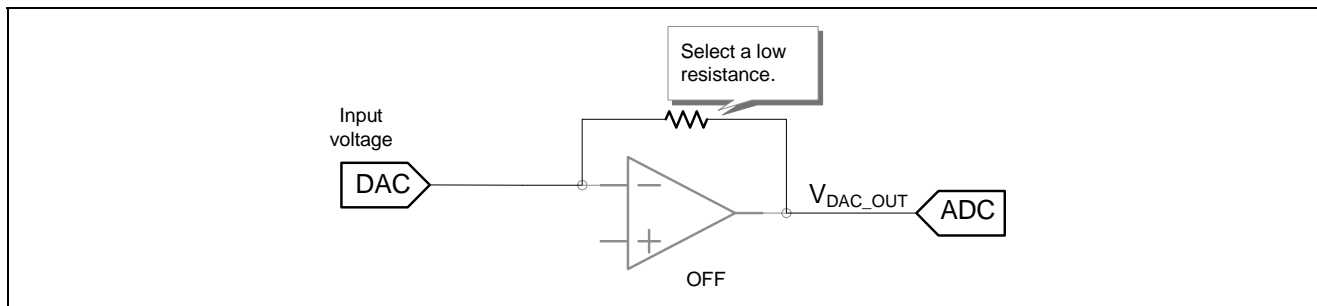
Figure 3-23   Measuring the D/A converter output voltage

Note   In Smart Analog IC 300, the minimum rated value of the feedback resistor is 20 kΩ. This is larger than the allowable input impedance (about 1 to 10 kΩ) of general A/D converters. Therefore, you need to take a measure such as installing a buffer amplifier to lower the input impedance of the A/D converter and setting a longer A/D converter sampling time. For details, see the user's manual of the microcontroller used.

(2)   **Measuring the configurable amplifier output voltage**

Connect the configurable amplifier as shown in Figure 3-24.

Figure 3-24   Offset voltage measurement when using an inverting or non-inverting amplifier configuration

Output the voltage set and measured in (1) from the D/A converter and input it to the configurable amplifier. Use an A/D converter to measure the voltage input to the configurable amplifier. Here, for the configurable amplifier gain, specify the value used in the actual system.

(3)   **Calculating the offset voltage**
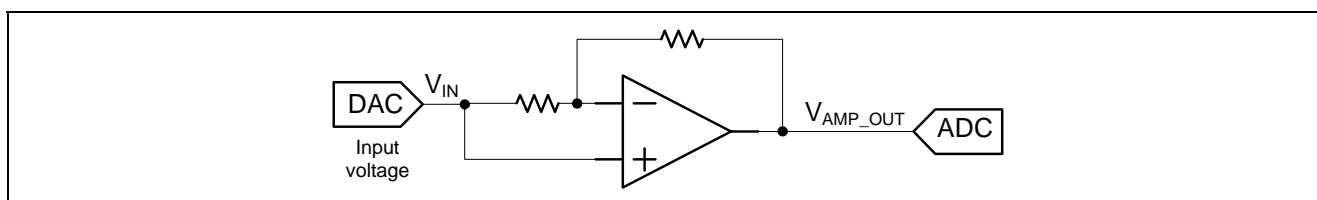
Calculate the offset voltage based on the voltage value measured by using the A/D converter.

In the configuration shown in Figure 3-24, the configurable amplifier output voltage (V_{AMP_OUT}) is expressed by using Formula 13, based on the gain in the inverting amplifier configuration (G_{Invert}) and the input voltage (V_{IN}).

$$
\begin{aligned}
V_{AMP\_OUT} &= \left(G_{Invert} + 1 \right) \cdot V_{IN} - G_{Invert} \cdot V_{IN} \\
&= V_{IN}
\end{aligned}
$$

...   Formula 13

Formula 13 indicates the perfect amplifier that does not cause the offset voltage. However, the voltage output from an actual amplifier generally includes the offset voltage. Formula 13 is transformed to Formula 14 and then to Formula 15, where the offset voltage is V_{offset_output}.

$$
V_{AMP\_OUT} = V_{IN} + V_{offset\_output}
$$

...   Formula 14

$$
V_{offset\_output} = V_{AMP\_OUT} - V_{IN}
$$

...   Formula 15

By substituting the V_{DAC_OUT} measured in (1) in V_{IN} and the value measured in (2) to V_{AMP_OUT} in Formula 15, the offset voltage can be obtained.

(4)   **Calculating the input-referred offset voltage**

Calculate the input-referred offset voltage (V_{offset_input}) based on the offset voltage (V_{offset_output}). The input-referred offset voltage is obtained by dividing the offset voltage by the gain. It is expressed by using Formula 16.

$$
V_{offset\_input} = \frac{V_{offset\_output}}{G_{Invert}}
$$

...   Formula 16

3.3.3   Measuring the gain error by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the gain error, based on the descriptions in *3.3.1*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Minimum value measurement**

Figure 3-25 to Figure 3-27 show how a circuit is configured for minimum value measurement and the circuit setting conditions.

Reference:
*.   *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration* or
     Table 3-3   D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration

Figure 3-25   Enable operation of configurable amplifier Ch1

Reference:
*:   *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration* or
     Table 3-3   D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration

Figure 3-26   Enable operation of configurable amplifier Ch2
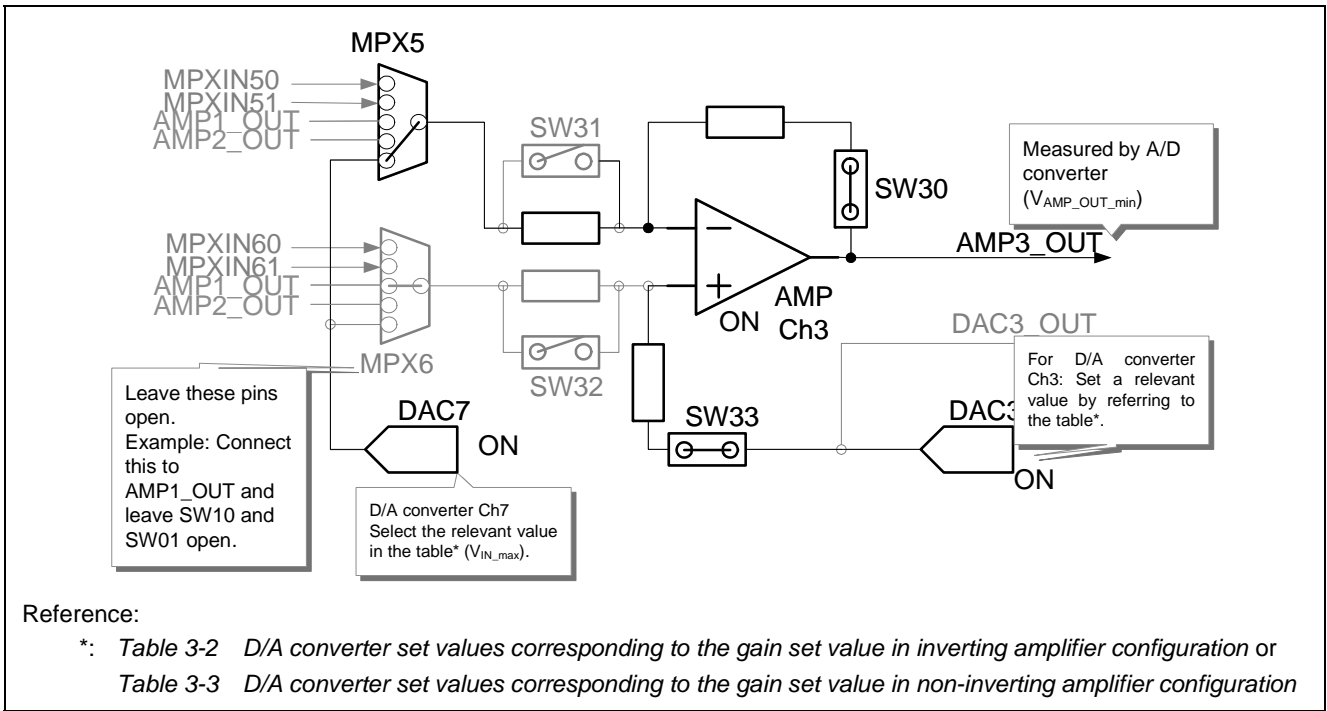
Figure 3-27   Enable operation of configurable amplifier Ch3

(2)   **Maximum value measurement**

Figures 3-28 and 3-29 show how a circuit is configured for maximum value measurement and the circuit setting conditions. Cha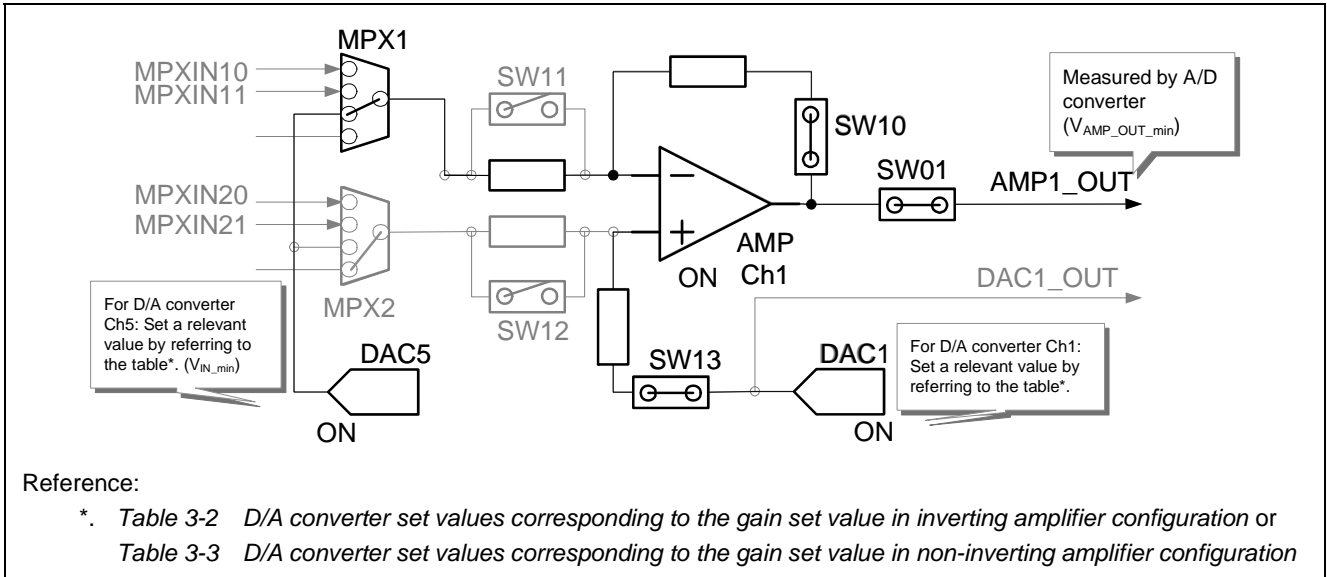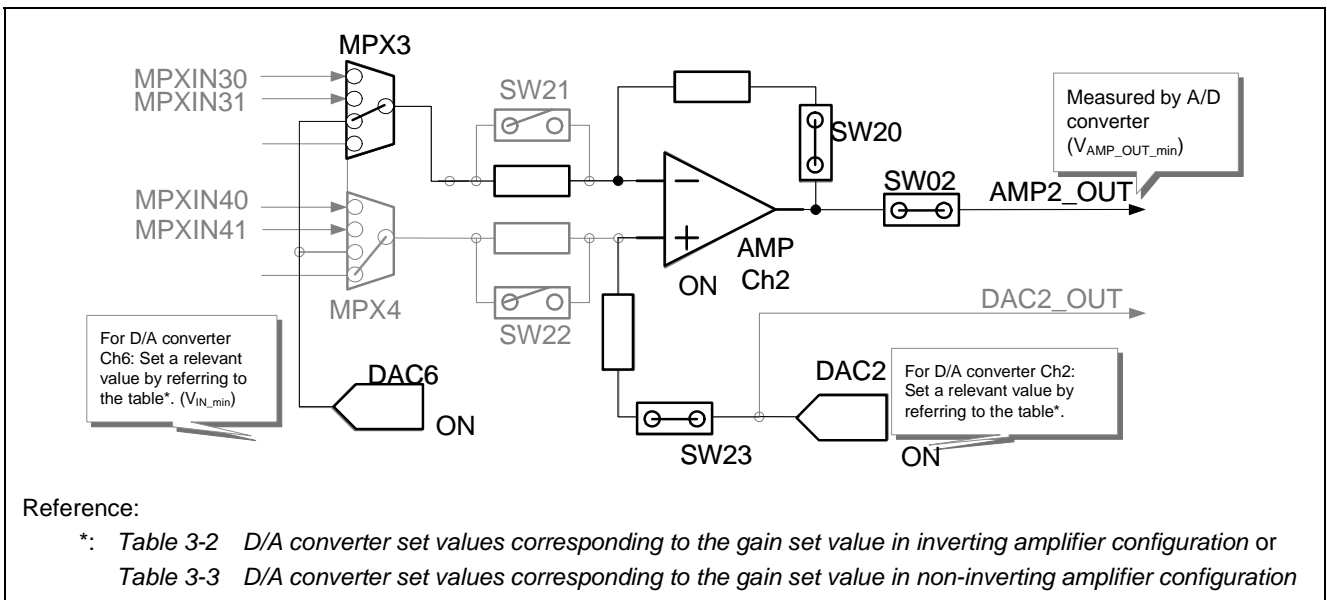nge the D/A converter output voltage to generate a differential voltage between the inverting input and non-inverting input. Here, the D/A converter whose setting is to be changed differs between the inverting amplifier configuration and the non-inverting amplifier configuration. For the value to be set, see Table 3-2 or Table 3-3.

Reference:

*1: *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration*

*2: *Figure 3-25   Enable operation of configurable amplifier Ch1*

*3: *Table 3-3   D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration*
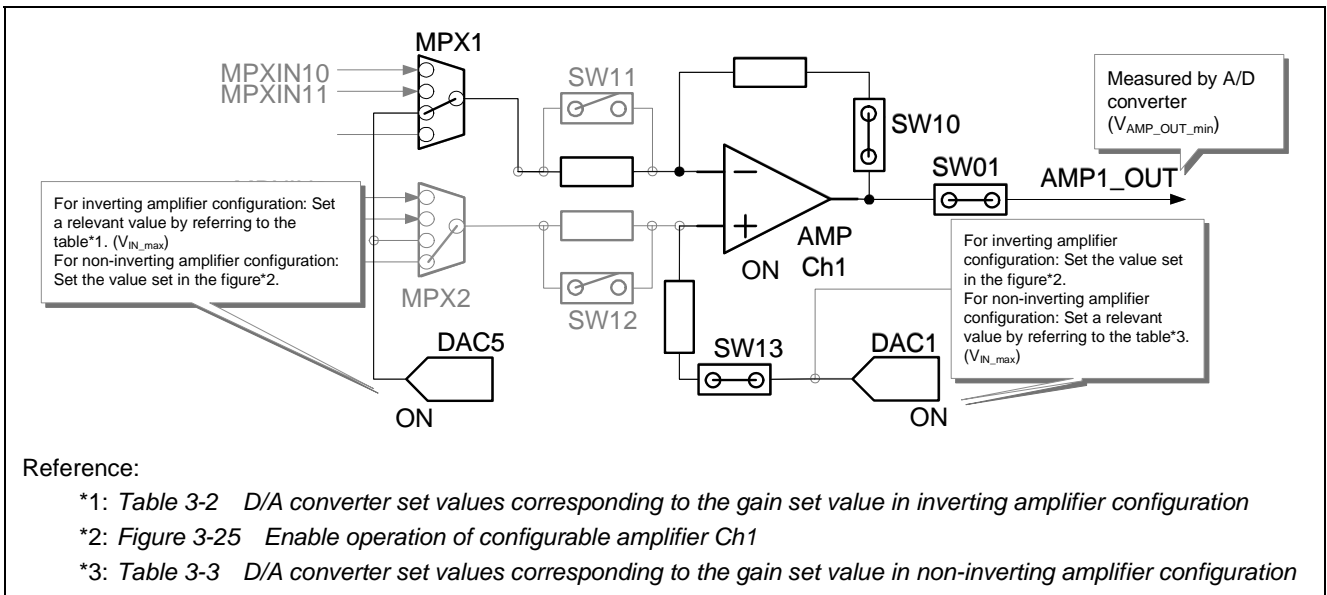
Figure 3-28   Configurable amplifier Ch1 for maximum value measurement

Reference:

*1: *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration*

*2: *Figure 3-26   Enable operation of configurable amplifier Ch2*

*3: *Table 3-3   D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration*
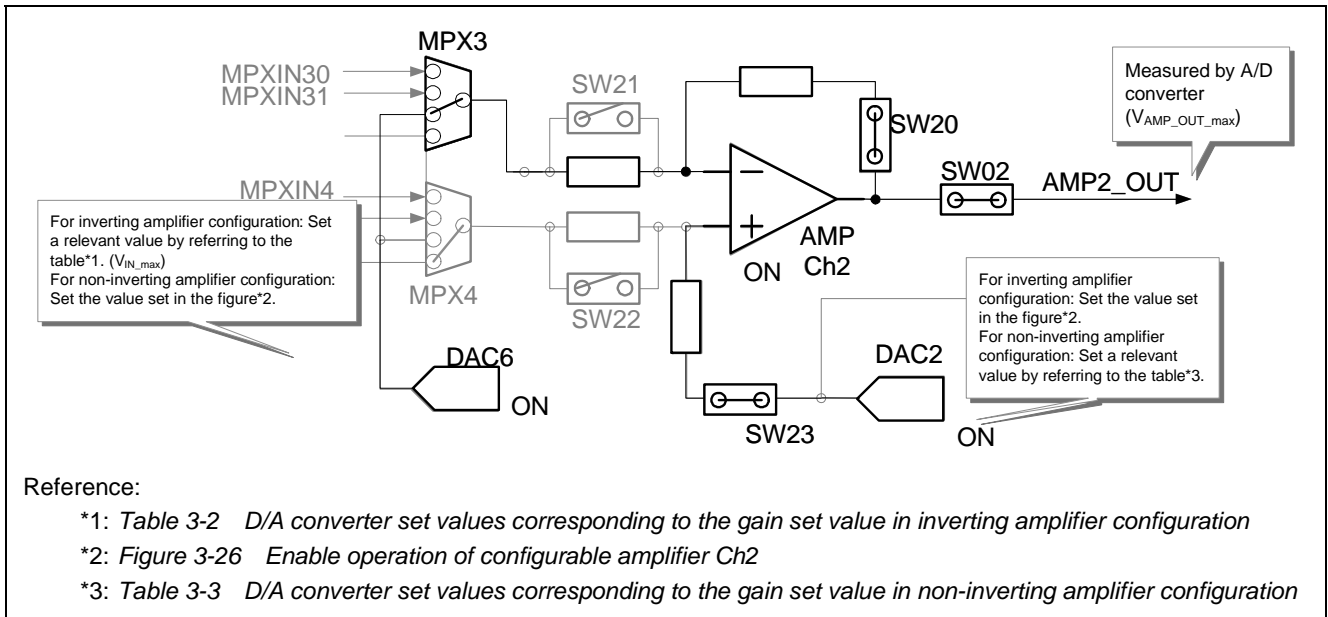
Figure 3-29   Configurable amplifier Ch2 for maximum value measurement

Reference:

*1: *Table 3-2   D/A converter set values corresponding to the gain set value in inverting amplifier configuration*

*2: *Figure 3-27   Enable operation of configurable amplifier Ch3*

*3: *Table 3-3   D/A converter set values corresponding to the gain set value in non-inverting amplifier configuration*

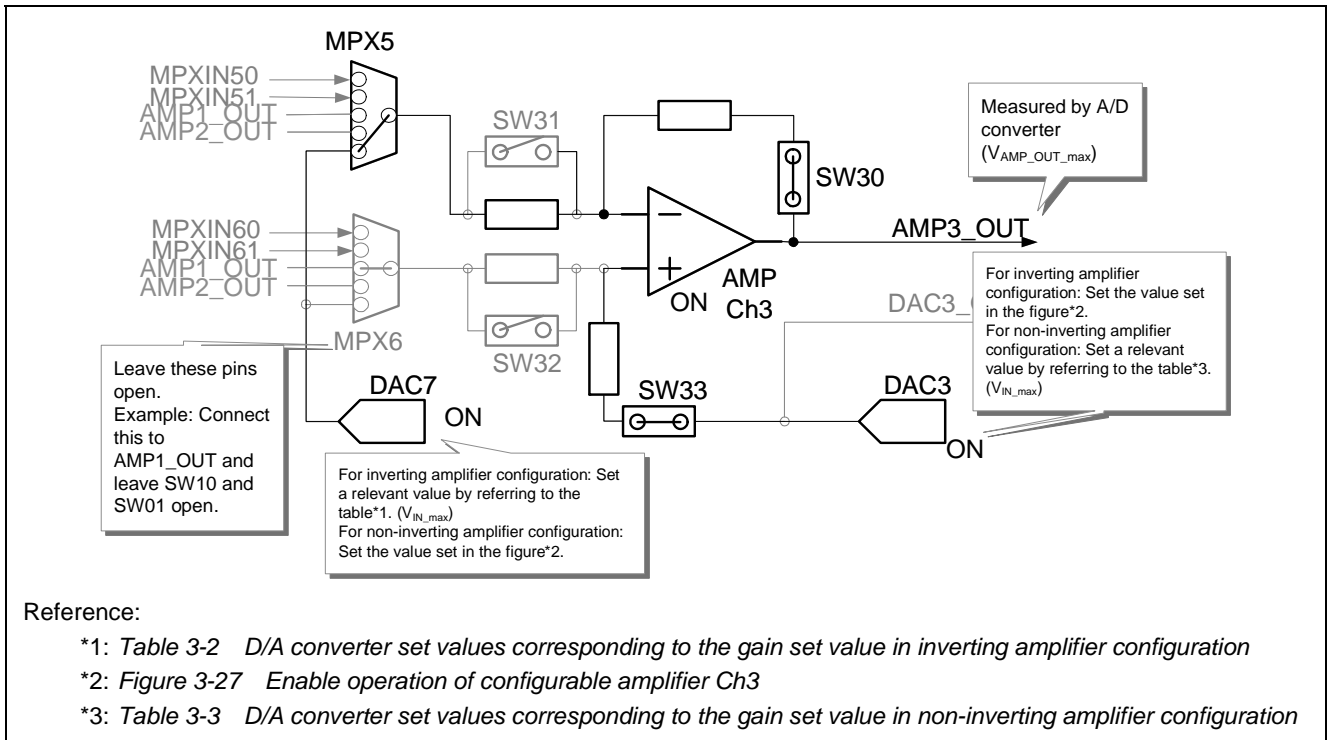**Figure 3-30   Configurable amplifier Ch3 for maximum value measurement**

(3) Calculating the gain

Calculate the configurable amplifier output voltage (V_{AMP_OUT}) based on the value measured by using the A/D converter (A/D-converted value). Based on the value measured by using the A/D converter (N_{AMP_OUT}) and power supply voltage (AV_{DD}), calculate the gain by using Formula 6.

$$ V_{AMP\_OUT} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} $$

... Formula 6

Note   n indicates the resolution of the A/D converter.

The minimum value voltage ($V_{AMP\_OUT\_min}$) and maximum value voltage ($V_{AMP\_OUT\_max}$) can be calculated by using Formula 6.

The input voltage (V_{IN}) is expressed by using Formula 7, based on the D/A converter set value (N_{DAC}), upper limit of the reference voltage (V_{VRT}), and lower limit of the reference voltage (V_{VRB}).

$$ V_{IN} = \left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \frac{N_{DAC}}{2^8} \right) + 2 \cdot V_{VRB} $$

... Formula 7

Note   8 indicates the number of bits as the unit of resolution.

Thus, gain G is expressed by using Formula 8, based on Formula 1, Formula 6, and Formula 7.

$$ G = \frac{(N_{AMP\_OUT\_Max} - N_{AMP\_OUT\_Min}) \cdot \dfrac{AV_{DD}}{2^n}}{\left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \dfrac{(N_{IN\_Max} - N_{IN\_Min})}{2^8} \right) + 2 \cdot V_{VRB}} $$

... Formula 8

(4) Averaging the results

If the results of measurement to be averaged (measurement is performed three times in this application note) are G_{First}, G_{Second}, and G_{Third} respectively, the average $G_{Average}$ is expressed by using Formula 9.

$$ G_{Average} = \frac{G_{First} + G_{Second} + G_{Third}}{3} $$

... Formula 9

(5) Calculating the gain error

Calculate the difference from the value prescribed in the specifications, and then calculate the gain based on the value measured and averaged in (4). For details, see *4.1.1 Calculating the gain error*.

3.3.4   Measuring the input-referred offset voltage by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the input-referred offset voltage, based on the descriptions in *3.3.2*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Measuring the D/A converter output voltage**

Figure 3-31 to Figure 3-33 show examples of measuring the voltage output from D/A converters incorporated in Smart Analog IC 300.
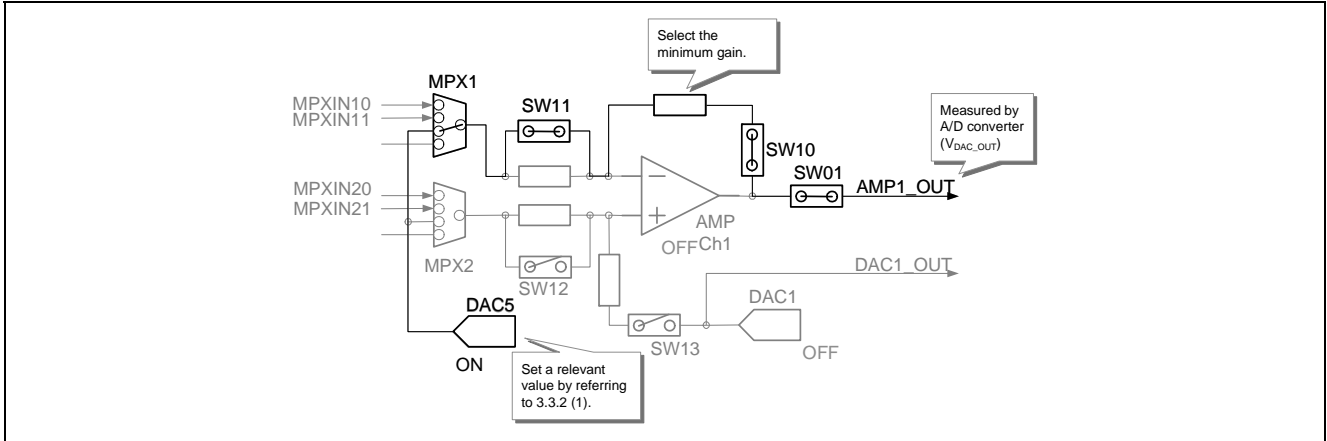

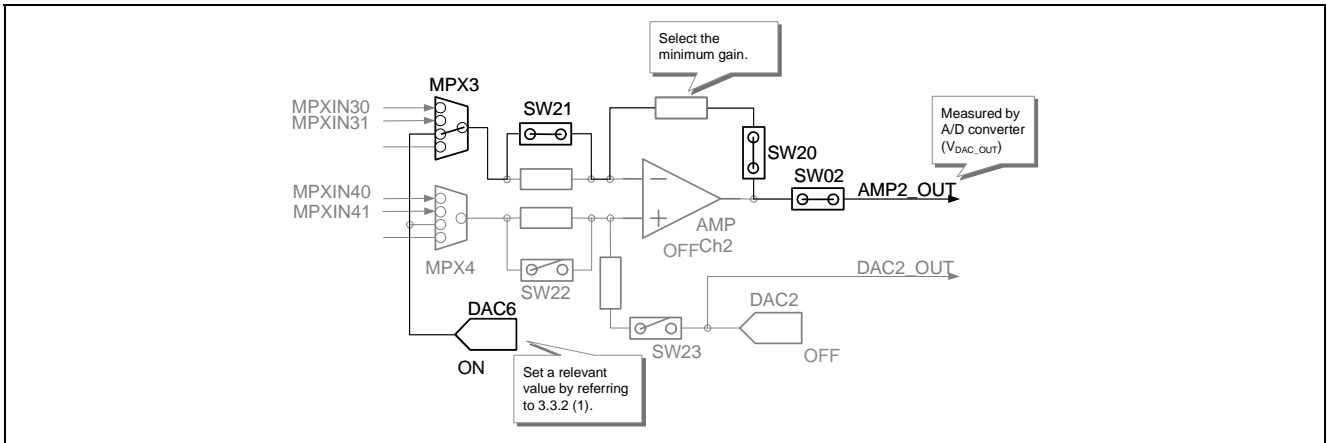**Figure 3-31   D/A converter Ch5 for output voltage measurement**

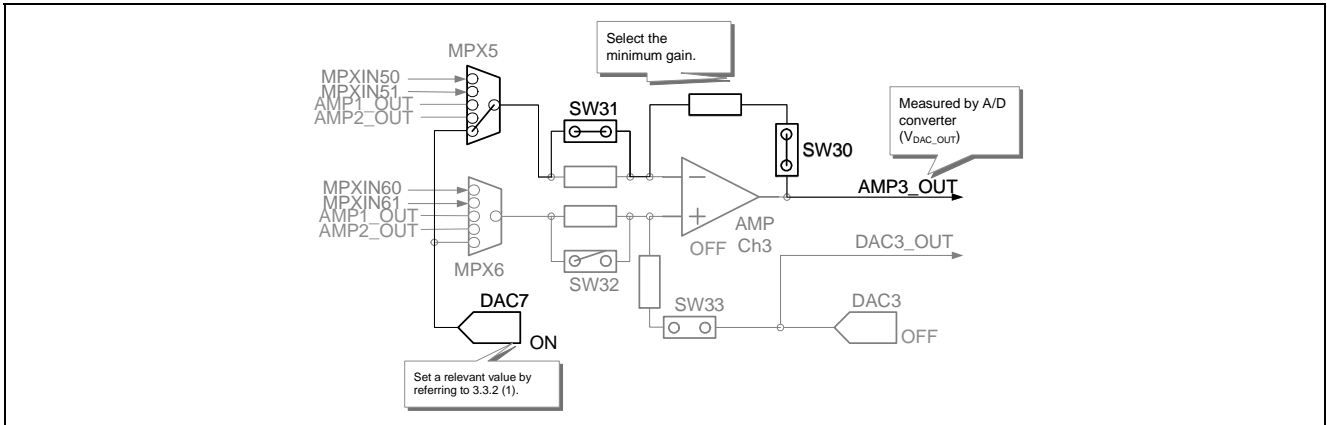**Figure 3-32   D/A converter Ch6 for output voltage measurement**

Figure 3-33   D/A converter Ch7 for output voltage measurement

Based on the value measured by using the A/D converter (A/D-converted value) (N_{DAC_OUT}) and power supply voltage (AV_{DD}), calculate the D/A converter output voltage (V_{DAC_OUT}) by using Formula 10.

$$V_{DAC\_OUT} = \frac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD} \qquad \qquad ... \qquad \text{Formula 10}$$

Note   n indicates the resolution of the A/D converter.

(2)   **Measuring the configurable amplifier output voltage**

Input the same voltage to the inverted input pin and the non-inverted input pin in the configurable amplifier, and measure the voltage output from the configurable amplifier.

Figure 3-34 to Figure 3-36 show examples of measuring the voltage output from the configurable amplifier incorporated in Smart Analog IC 300.
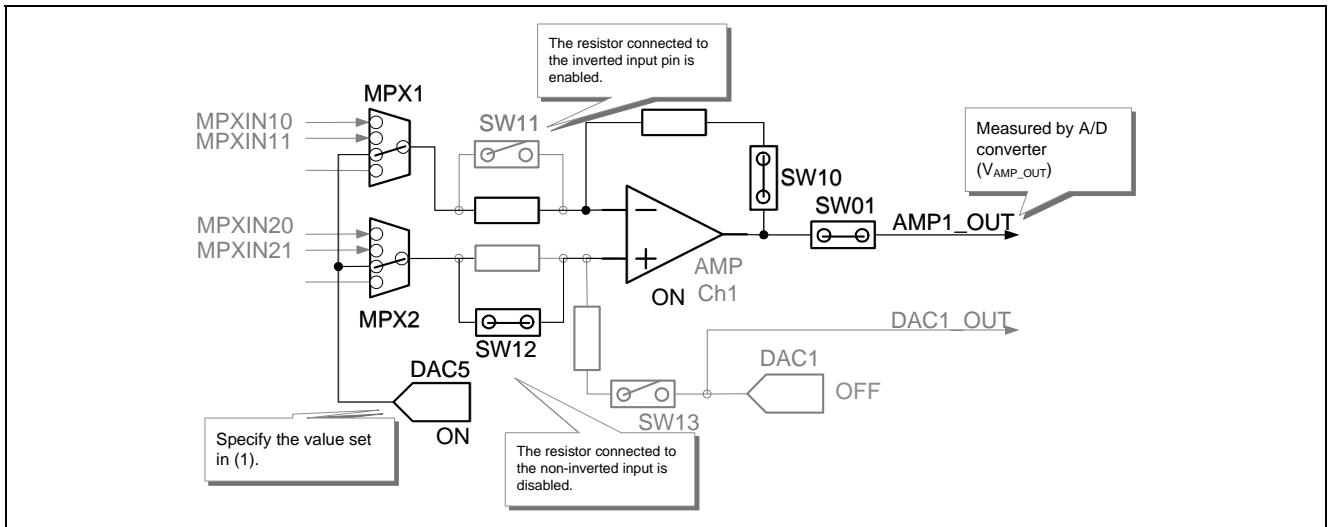

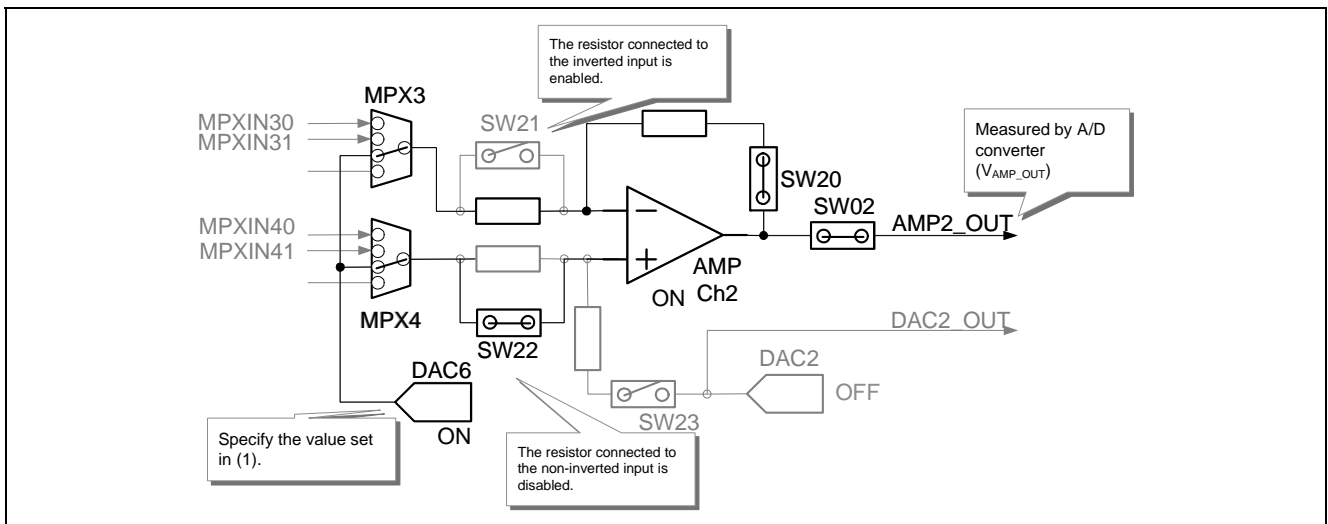**Figure 3-34   Configurable amplifier Ch1 for output voltage measurement**

Figure 3-35   Configurable amplifier Ch2 for output voltage measurement
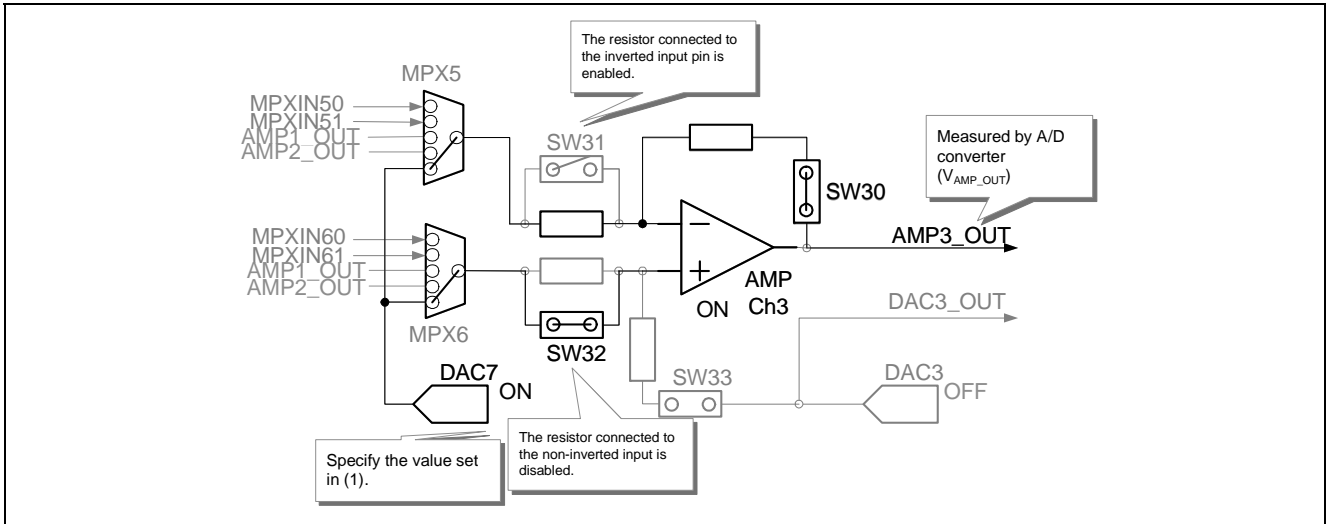
Figure 3-36   Configurable amplifier Ch3 for output voltage measurement

Based on the value measured by using the A/D converter (A/D-converted value), calculate the configurable amplifier output voltage (V_{AMP_OUT}) by using Formula 6.

$$V_{AMP\_OUT} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} \qquad \text{...} \qquad \text{Formula 6}$$

Note   n indicates the resolution of the A/D converter.

(3)   **Calculating the offset voltage**

Calculate the offset voltage by substituting the values obtained in *(1) Measuring the D/A converter (with an external pin) output voltage* and *(2) Measuring the configurable amplifier output voltage* in Formula 15. Substituting Formula 6 and Formula 10 in Formula 15 results in Formula 11.

$$V_{offset\_output} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} - \frac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD} \qquad \text{...} \qquad \text{Formula 11}$$

(4)   **Calculating the input-referred offset voltage**

Calculate the input-referred offset voltage based on the offset voltage. The input-referred offset voltage can be calculated by using Formula 16 and Formula 11, which results in Formula 17. G_{diff} is the gain that has been used for measurement.

$$V_{Offset} = \frac{\dfrac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} - \dfrac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD}}{G_{invert}} \qquad \text{...} \qquad \text{Formula 17}$$

3.4   Measurement procedure when using an instrumentation amplifier configuration

This section describes the procedure for measuring the gain error and the input-referred offset voltage when using the configurable amplifier in the instrumentation amplifier configuration.

3.4.1   Procedure for measuring the gain error

The procedure for measuring the gain error is the same as that used in the differential amplifier configuration (see *3.2.1*). For details about the measurement flow and its description, see *3.2.1*.

(1)   **Determine the voltage input to the configurable amplifier (voltage output from the D/A converter)**

Based on the concept described in *3.2.1 (1)*, determine the voltage input to the configurable amplifier (the voltage output from the D/A converter).

When using the configurable amplifier as an instrumentation amplifier, use three D/A converter channels. For minimum value measurement, set all three D/A converter channels to x0H (x = 2 to 4) (digital input value). For minimum value measurement, set the D/A converters by referring to Table 3-4.

(2)   **Minimum value measurement**

Connect separate D/A converter channels to supply the input voltage on the inverting input connected to the preamplifier, and the input voltage and reference voltage on the non-inverting input. Specify the same voltage to be output from all the D/A converter channels (V_{IN_min}). Use the result measured under these conditions (configurable amplifier output voltage) as the minimum value voltage ($V_{AMP\_OUT\_min}$).
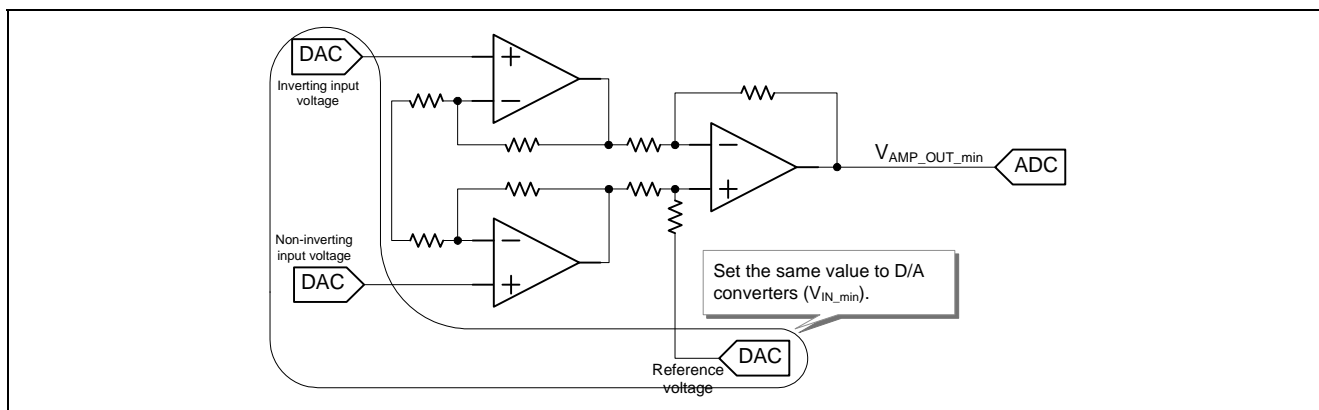
Figure 3-37   Minimum value measurement

(3)   **Maximum value measurement**

Set the D/A converter connected to the non-inverting input connected to the preamplifier to a value greater than or equal to the value set for minimum value measurement. Specify the value to set by referring to Table 3-4. Do not change the input voltage on the inverting input and the reference voltage on the non-inverting input. Here, the voltage supplied to the non-inverting input is expressed as V_{IN_max}, and the configurable amplifier output voltage obtained as a result of measurement is expressed as the maximum value voltage ($V_{AMP\_OUT\_max}$).

Reference:
   *1: *Figure 3-37   Minimum value measurement*
   *2: *Table 3-4   D/A converter set values corresponding to the gain set value in instrumentation amplifier configuration*

Figure 3-38   Maximum value measurement

Table 3-4 D/A converter set values corresponding to the gain set value in instrumentation amplifier configuration

Number of averaging times	Reference voltage on inverting input (preamplifier)	Input voltage on non-inverting input (preamplifier) (per gain set value)						
		0-3 (15.5-21.5dB)	4 (23.5dB)	5 (25.5dB)	6 (27.5dB)	7 (29.5dB)	8 (31.5dB)	9 (33.5dB)
1st	20H	2FH	2CH	2AH	27H	26H	25H	23H
2nd	30H	3FH	3CH	3AH	37H	36H	35H	33H
3rd	40H	4FH	4CH	4AH	47H	46H	45H	43H

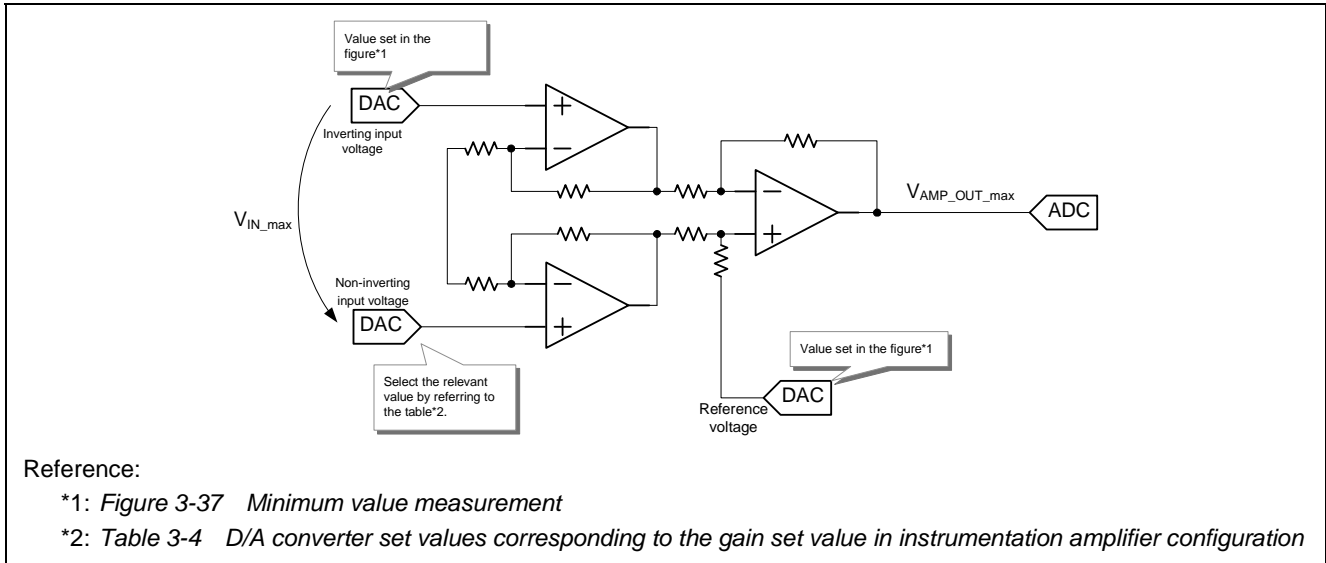Note   For the maximum value measurement, the value set to the non-inverting input connected to the preamplifier is prescribed so that the difference from the voltage of the inverting input connected to the preamplifier becomes the maximum, within the allowable A/D converter input range. The value is measured three times and the results are averaged.

(4)   **Calculating the gain**

Calculate the gain based on the minimum and maximum value voltages and the voltage supplied to the non-inverting input (D/A converter output voltage). Generally, a gain is obtained by dividing the output voltage by the input voltage. However, the gain obtained by using division includes the offset voltage. In this application note, relative values are used to calculate the gain that does not include the offset voltage. Gain G is expressed as shown in Formula 1 below.

$$G = \frac{V_{AMP\_OUT\_max} - V_{AMP\_OUT\_min}}{V_{IN\_max} - V_{IN\_min}}$$ ...   Formula 1

(5)   **Averaging the results**

To improve the measurement precision, change the voltage level supplied from the D/A converters and repeat steps (1) to (4) to measure the value multiple times (three times in the examples shown in this application note). After measurement is performed three times, average the obtained data to obtain the gain.

(6) **Calculating the gain error**

Calculate the difference from the value prescribed in the specifications, and then calculate the gain based on the value measured and averaged in (5). For details, see *4.1.1 Calculating the gain error*.

3.4.2   Procedure for measuring the input-referred offset voltage

Input the same voltage to the inverted input pin and the non-inverted input pin in the configurable amplifier, and measure the voltage output from the configurable amplifier. Calculate the offset voltage by measuring the difference between the input voltage and output voltage. The input-referred offset voltage is obtained by dividing the offset voltage by the amplifier gain.

When the configurable amplifier is used as an instrumentation amplifier, multiple amplifiers are used. At first, measure the offset voltage of each amplifier. Then, add up the offset voltage of each amplifier and divide them to calculate the input-referred offset voltage in the instrumentation amplifier. Figure 3-39 shows the input-referred offset voltage measurement flow.
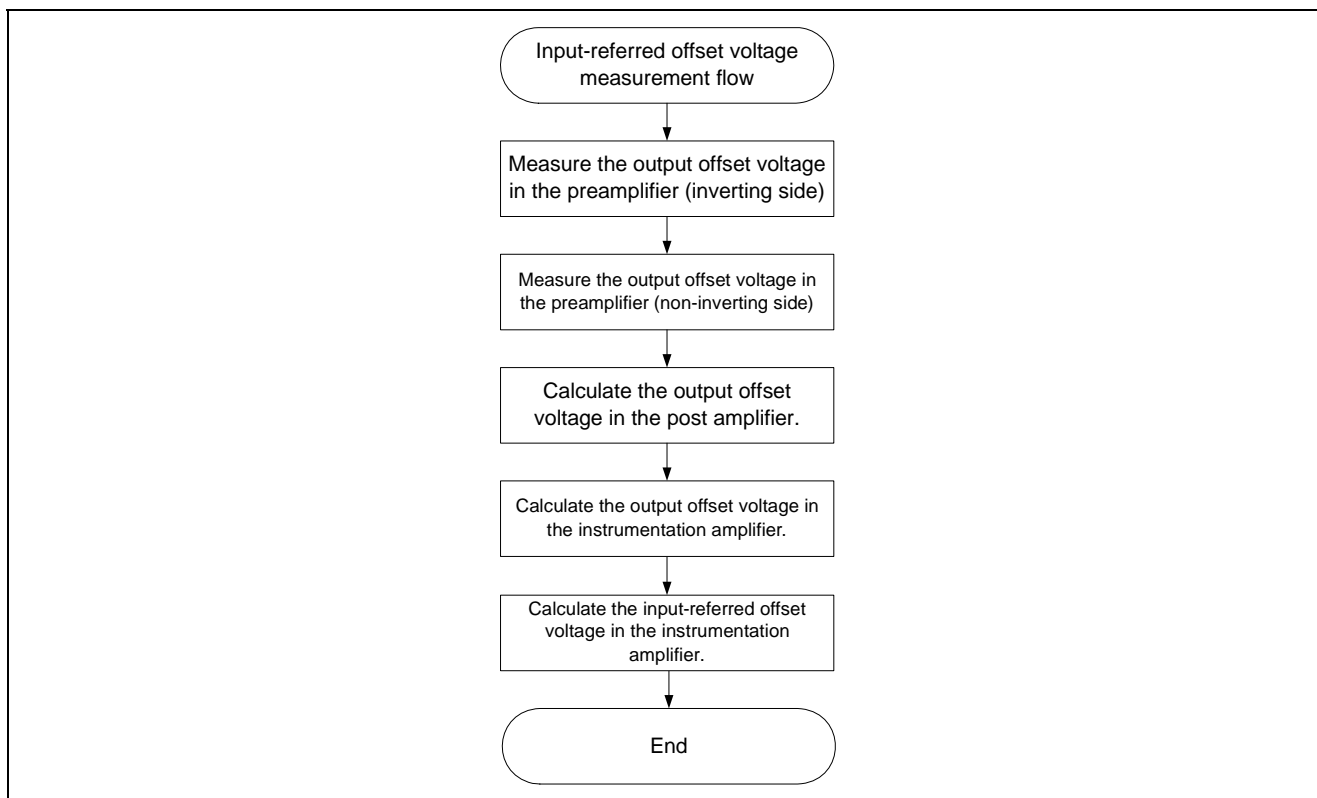
Figure 3-39   Input-referred offset voltage measurement flow

The procedure is described below in detail based on the flow shown in Figure 3-39.

(1) **Measure the offset voltage in the preamplifier (connected to inverting input)**

When the configurable amplifier is used as an instrumentation amplifier, the preamplifier (connected to inverting input) is used as a non-inverting amplifier with a gain of 9.5 dB. Therefore, you need to calculate the offset voltage (V_{offset_pre1}) in the inverting amplifier configuration according to the procedure shown in *3.3.2*.

(2) **Measure the offset voltage in the preamplifier (connected to inverting input)**

When the configurable amplifier is used as an instrumentation amplifier, the preamplifier (connected to non-inverting input) is used as a non-inverting amplifier with a gain of 9.5 dB. Therefore, you need to calculate the offset voltage (V_{offset_pre2}) in the inverting amplifier configuration according to the procedure shown in *3.3.2*.

(3)   **Offset voltage in the post amplifier**

When the configurable amplifier is used as an instrumentation amplifier, the post amplifier is used as a differential amplifier. Therefore, you need to calculate the offset voltage (V_{offset_post}) according to the procedure shown in *3.2.2*. Here, for the post amplifier gain, specify the value used in the actual system.
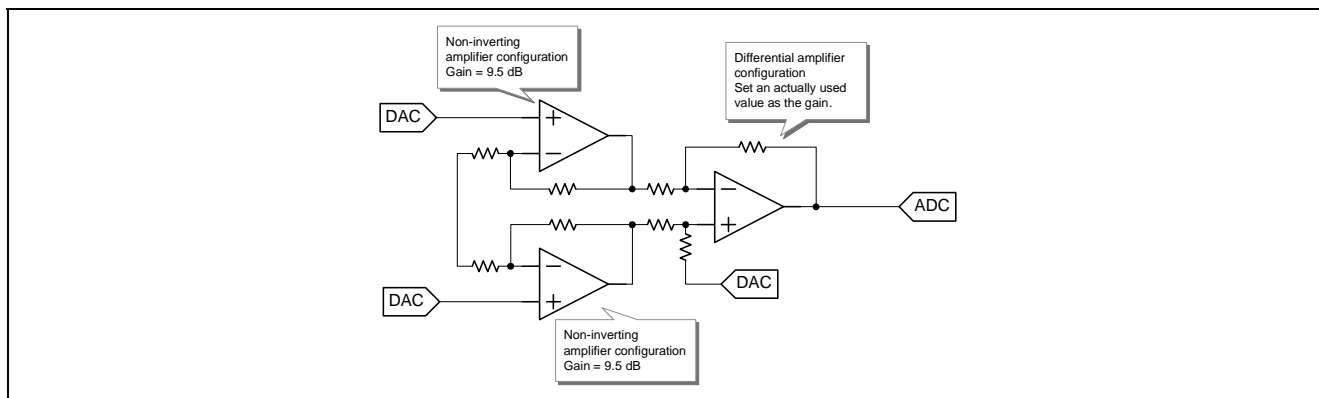
Figure 3-40   Measuring the offset voltage when using an instrumentation amplifier configuration

(4)   **Offset voltage in the instrumentation amplifier**

Calculate the offset value of the instrumentation amplifier based on the value calculated in (1) to (3). If the post amplifier gain is G_{diff}, the offset value of the instrumentation amplifier ($V_{offset\_output\_inst}$) is expressed by using Formula 18.

$$V_{offset\_output\_inst} = \left(V_{offset\_pre2} - V_{offset\_pre1} + \frac{V_{offset\_post}}{G_{diff}} \right) \cdot G_{diff} \qquad ... \qquad \text{Formula 18}$$

(5)   **Input-referred offset voltage in the instrumentation amplifier**

Calculate the input-referred offset voltage (V_{offset_inst}) based on the offset voltage ($V_{offset\_output\_inst}$). The input-referred offset voltage is obtained by dividing the offset voltage by the gain. Based on the instrumentation amplifier gain (G_{inst}), the input-referred offset voltage (V_{offset_inst}) is expressed by using Formula 19.

$$V_{offset\_inst} = \frac{V_{offset\_output\_inst}}{G_{inst}} \qquad ... \qquad \text{Formula 19}$$

3.4.3   Measuring the gain error by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the gain error, based on the descriptions in *3.4.1*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Minimum value measurement**

Figure 3-41 shows how a circuit is configured for minimum value measurement and the circuit setting conditions.
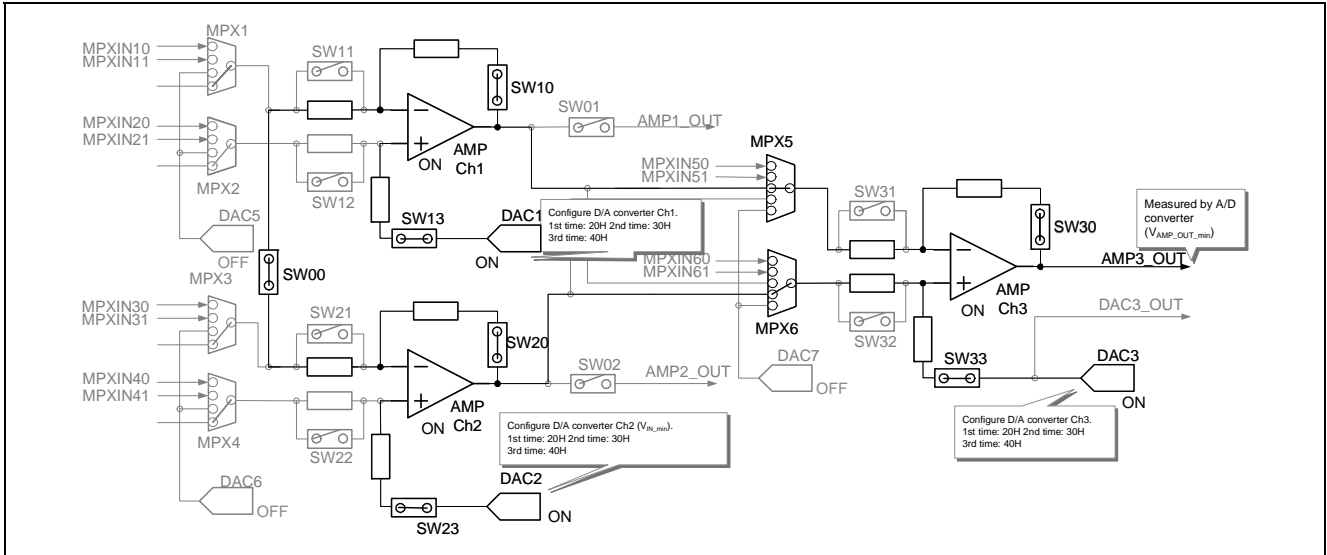
Figure 3-41   Minimum value measurement in an instrumentation amplifier configuration

(2)   **Maximum value measurement**

Figure 3-42 shows how a circuit is configured for maximum value measurement and the circuit setting conditions. Do not change the input voltage on the inverting input and the reference voltage on the non-inverting input set in *(1) Maximum value measurement*.
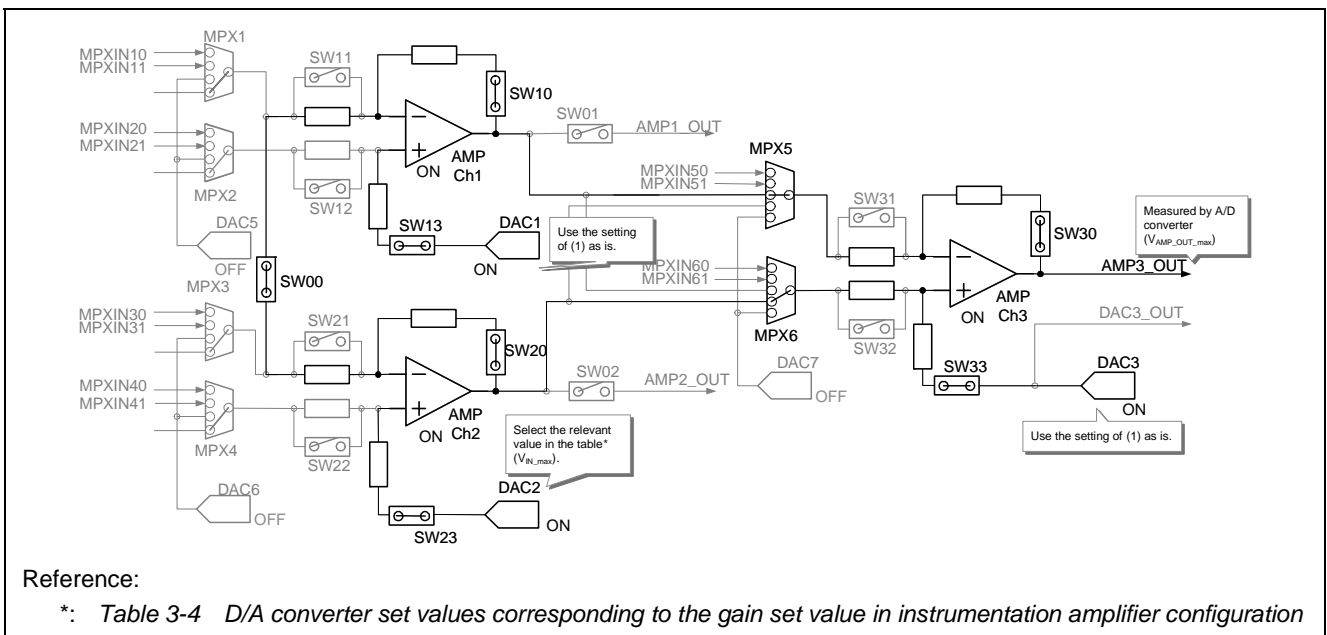
Reference:

*:   *Table 3-4   D/A converter set values corresponding to the gain set value in instrumentation amplifier configuration*

Figure 3-42   Maximum value measurement in an instrumentation amplifier configuration

(3)   **Calculating the gain**

Calculate the configurable amplifier output voltage (V_{AMP_OUT}) based on the value measured by using the A/D converter (A/D-converted value). Based on the value measured by using the A/D converter (N_{AMP_OUT}) and power supply voltage (AV_{DD}), calculate the gain by using Formula 6.

$$V_{AMP\_OUT} = \frac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} \qquad ... \quad \text{Formula 6}$$

Note   n indicates the resolution of the A/D converter.

The minimum value voltage ($V_{AMP\_OUT\_min}$) and maximum value voltage ($V_{AMP\_OUT\_max}$) can be calculated by using Formula 6.

The input voltage (V_{IN}) is expressed by using Formula 7, based on the D/A converter set value (N_{DAC}), upper limit of the reference voltage (V_{VRT}), and lower limit of the reference voltage (V_{VRB}).

$$V_{IN} = \left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \frac{N_{DAC}}{2^8} \right) + 2 \cdot V_{VRB} \qquad ... \quad \text{Formula 7}$$

Note   8 indicates the number of bits as the unit of resolution.

Thus, instrumentation amplifier gain G is expressed by using Formula 8, based on Formula 1, Formula 6, and Formula 7.

$$G = \frac{(N_{AMP\_OUT\_Max} - N_{AMP\_OUT\_Min}) \cdot \dfrac{AV_{DD}}{2^n}}{\left((V_{VRT} - V_{VRB}) \cdot 2 \cdot \dfrac{(N_{IN\_Max} - N_{IN\_Min})}{2^8} \right) + 2 \cdot V_{VRB}} \qquad ... \quad \text{Formula 8}$$

(4)   **Averaging the results**

If the results of measurement to be averaged (measurement is performed three times in this application note) are G_{First}, G_{Second}, and G_{Third} respectively, the average $G_{Average}$ is expressed by using Formula 9.

$$G_{Average} = \frac{G_{First} + G_{Second} + G_{Third}}{3} \qquad ... \quad \text{Formula 9}$$

(5)   **Calculating the gain error**

Calculate the difference from the value prescribed in the specifications, and then calculate the gain based on the value measured and averaged in (4). For details, see *4.1.1 Calculating the gain error*.

3.4.4   Measuring the input-referred offset voltage by using Smart Analog IC 300

This section describes how to configure the actual circuit by using Smart Analog IC 300 and how to calculate the input-referred offset voltage, based on the descriptions in *3.4.2*. For the connection between Smart Analog IC 300 and the microcontroller, see Figure 3-1.

(1)   **Measure the offset voltage in the preamplifier (connected to inverting input)**

Calculate the offset voltage of configurable amplifier Ch1 in Smart Analog IC 300. Measure the voltage output from configurable amplifier Ch1 in a non-inverting amplifier configuration with a gain of 9.5 dB. For how to perform measurement and the circuit connection diagram, see *3.3.4*.

(2)   **Measure the offset voltage in the preamplifier (connected to non-inverting input)**

Calculate the offset voltage of configurable amplifier Ch2 in Smart Analog IC 300. Measure the voltage output from configurable amplifier Ch2 in a non-inverting amplifier configuration with a gain of 9.5 dB. For how to perform measurement and the circuit connection diagram, see *3.3.4*.

(3)   **Offset voltage in the post amplifier**

Calculate the offset voltage of configurable amplifier Ch3 in Smart Analog IC 300. Measure the voltage output from configurable amplifier Ch3 in a differential amplifier configuration. Here, for gain of amplifier 3, specify the value used in the actual system. For how to perform measurement and the circuit connection diagram, see *3.2.4*.

(4)   **Offset voltage in the instrumentation amplifier**

Calculate the offset voltage of each configurable amplifier as shown in (1) to (3), and then calculate the offset voltage of the instrumentation amplifier by using Formula 18.

(5)   **Input-referred offset voltage in the instrumentation amplifier**

Calculate the input-referred offset voltage of the instrumentation amplifier based on the value calculated in (4). Use Formula 19.

4.   Example of implementation

This section shows an example of measurement by using the procedure shown in *3.2.3* and *3.2.4*. In the example below, measurement is performed under the conditions shown in Table 4-1. Use this data for reference only. When using this data in actual measurement, thoroughly evaluate the operation in advance.

Table 4-1   Conditions Under Which Operation Has Been Verified

| Conditions		Set value
Configurable amplifier	Channels used	Ch1
	Amplifier configuration	Differential amplifier
	Specified gain	20 dB (x10)
D/A converter	Channel connected to inverted input pin	Ch6
	Channel connected to non-inverted input pin	Ch5
	D/A converter set value for measuring offset voltage	80H (128)
Supply voltage		3.3 V
Microcontroller used		RL78/G1A
A/D converter resolution		12 bits
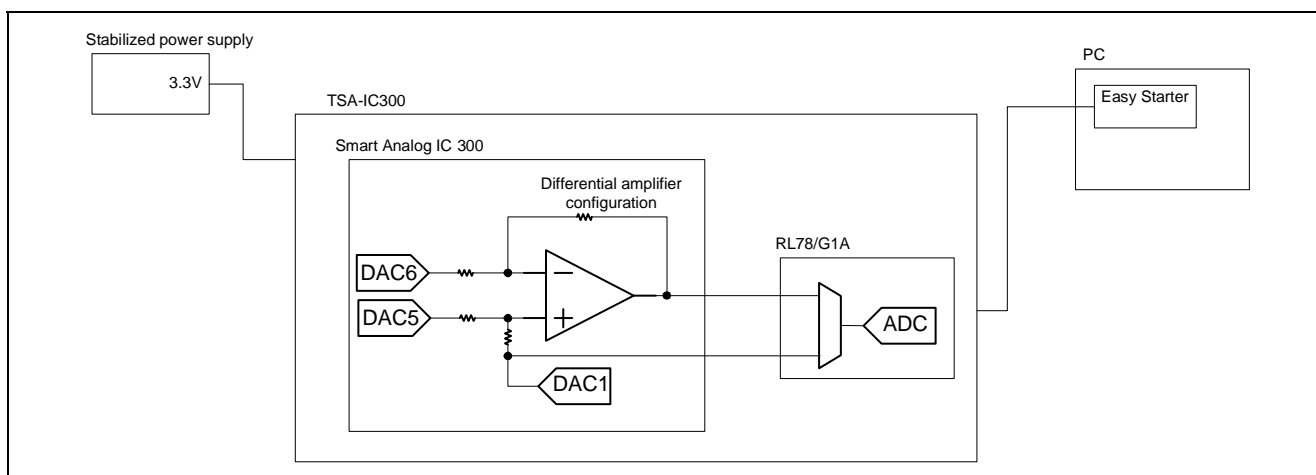
Figure 4-1   Block diagram for measurement

4.1   Examples for calculating errors

4.1.1   Calculating the gain error

The following shows an example for measuring the gain error. Measure the gain error according to the procedure shown in *3.2.3*. For the value set to the D/A converter, see Table 4-2.

Table 4-2   D/A converter set value

Count	Value set to D/A converter channels Ch1 and Ch6		Value set to D/A converter channel Ch5	
	Min. value (LSB)	Max. value (LSB)	Min. value (LSB)	Max. value (LSB)
1st	20H	20H	20H	2FH
2nd	30H	30H	30H	3FH
3rd	40H	40H	40H	4FH

Apply the voltage output from the D/A converters when the values shown in Table 4-2 are set, to the configurable amplifier as the input voltage and reference voltage. The result of the configurable amplifier output voltage is shown in Table 4-3.

Table 4-3   Measured configurable amplifier output voltage

Count	Value measured by A/D converter	
	With min. value applied	With max. value applied
1st	520	2890
2nd	776	3144
3rd	1034	3403

The gain can be calculated by substituting the measured values in Table 4-2 and Table 4-3 in Formula 8. Table 4-4 shows the calculation result.

Table 4-4   Calculated gain for configurable amplifier Ch1.

Count	Gain (times)
1st	9.875
2nd	9.867
3rd	9.871

Apply the measured values in Table 4-4 to Formula 9. The result is as shown in Formula 20.

$$G_{Average} = \frac{9.875 + 9.867 + 9.871}{3}$$
$$= 9.87 times$$

... Formula 20

In this example, the multiplication factor of the gain in the actual measurement results in x9.87. The specified gain is 20 dB (x10), so the gain error (difference from the specifications) is −1.3%.

4.1.2   Calculating the input-referred offset voltage

The following shows an example of calculating the input-referred offset voltage.

Calculate the voltage output from D/A converter Ch1 according to the procedure shown in *3.2.4 (1)*. Table 4-5 shows the value measured by using an A/D converter.

Table 4-5   Measured D/A converter Ch1 output voltage

Value set to D/A converter channel Ch5	A/D-converted value N_{DAC_OUT}
80H (128)	2047

Measure the voltage output from configurable amplifier Ch1 according to the procedure shown in *3.2.4 (2)*. Table 4-6 shows the value measured by using an A/D converter.

Table 4-6   Measured configurable amplifier Ch1 output voltage

Value set to D/A converter channels Ch1 and Ch5	A/D-converted value N_{AMP_OUT}
80H (128)	2069

Calculate the input-referred offset voltage based on the measured value.

By substituting the measured values in Table 4-5 and Table 4-6 in Formula 12, the input-referred offset voltage is as shown in Formula 21.

$$V_{Offset} = \frac{\dfrac{N_{AMP\_OUT}}{2^n} \cdot AV_{DD} - \dfrac{N_{DAC\_OUT}}{2^n} \cdot AV_{DD}}{G}$$

$$= \frac{3.3}{2^{12}} \cdot \frac{2069 - 2047}{9.87}$$

$$\cong 1.80 mV$$

... Formula 21

4.2   Examples for calculating the input voltage

Calculate the input voltage based on the gain and the input-referred offset voltage calculated in section 4.1. The voltage output from the configurable amplifier is also required for calculating the voltage input to the configurable amplifier. This example shows the case where the output voltage is A/D-converted and 3000LSB is obtained.

Calculation of the differential voltage input to the differential amplifier from the A/D conversion result is expressed by using the following:

$$V_{IN+} - V_{IN-} = \frac{V_{AMP\_OUT} - V_{bias}}{G} - V_{offset} \qquad \text{...} \qquad \text{Formula 22}$$

$$V_{IN+} - V_{IN-} = \frac{\dfrac{N_{AMP\_OUT}}{2^{12}} \cdot AV_{DD} - \dfrac{N_{DAC\_OUT}}{2^{8}} \cdot AV_{DD}}{G} - V_{offset} \qquad \text{...} \qquad \text{Formula 23}$$

The measurement conditions in 4.1 and the calculated values are shown below.

Table 4-7   Conditions

Conditions	Set value		Measured value[Note]	Result of measurement in 4.1	
AV$_{DD}$	Specified gain	Reference voltage	A/D-converted value	Calculated gain	Offset voltage
3.3 V	x10	80H (128)	3000LSB	x9.87	1.80 mV

Note: This is the A/D-converted voltage output from the configurable amplifier.

If the gain error and offset voltage cannot be calculated and their effect cannot be applied (G = x10, V$_{offset}$ = 0), the difference voltage input to the differential amplifier is determined to be 76.7 mV, by using formula 23.

$$V_{IN+} - V_{IN-} = \frac{\dfrac{3000}{4096} \cdot 3.3 - \dfrac{128}{256} \cdot 3.3}{10} - 0 \qquad \text{...} \qquad \text{Formula 24}$$

$$V_{IN+} - V_{IN-} = 76.7 mV \qquad \text{...} \qquad \text{Formula 25}$$

On the other hand, if the effect of the gain error and offset voltage can be applied (G = x9.87, V$_{offset}$ = 1.80 mV), the difference voltage input to the differential amplifier is determined to be 75.9 mV, by using formula 23.

$$V_{IN+} - V_{IN-} = \frac{\dfrac{3000}{4096} \cdot 3.3 - \dfrac{128}{256} \cdot 3.3}{9.87} - 1.80m \qquad \text{...} \qquad \text{Formula 26}$$

$$V_{IN+} - V_{IN-} = 75.9 mV \qquad \text{...} \qquad \text{Formula 27}$$

Comparison of Formula 25 and Formula 27 are as shown in Formula 28.

$$V_{Error} = \frac{76.7mV - 75.9mV}{75.9mV} \cdot 100$$

$$= 1.05\%$$

...   Formula 28

In this example, by correcting the gain error and offset voltage, the error is reduced by 0.8 mV as the absolute value for the sensing signal, and by 1.05% as the relative precision.

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1. Handling of Unused Pins

   Handle unused pins in accordance with the directions given under Handling of Unused Pins in the manual.

   — The input pins of CMOS products are generally in the high-impedance state. In operation with an unused pin in the open-circuit state, extra electromagnetic noise is induced in the vicinity of LSI, an associated shoot-through current flows internally, and malfunctions occur due to the false recognition of the pin state as an input signal become possible. Unused pins should be handled as described under Handling of Unused Pins in the manual.

2. Processing at Power-on

   The state of the product is undefined at the moment when power is supplied.

   — The states of internal circuits in the LSI are indeterminate and the states of register settings and pins are undefined at the moment when power is supplied.
   In a finished product where the reset signal is applied to the external reset pin, the states of pins are not guaranteed from the moment when power is supplied until the reset process is completed.
   In a similar way, the states of pins in a product that is reset by an on-chip power-on reset function are not guaranteed from the moment when power is supplied until the power reaches the level at which resetting has been specified.

3. Prohibition of Access to Reserved Addresses

   Access to reserved addresses is prohibited.

   — The reserved addresses are provided for the possible future expansion of functions. Do not access these addresses; the correct operation of LSI is not guaranteed if they are accessed.

4. Clock Signals

   After applying a reset, only release the reset line after the operating clock signal has become stable. When switching the clock signal during program execution, wait until the target clock signal has stabilized.

   — When the clock signal is generated with an external resonator (or from an external oscillator) during a reset, ensure that the reset line is only released after full stabilization of the clock signal. Moreover, when switching to a clock signal produced with an external resonator (or by an external oscillator) while program execution is in progress, wait until the target clock signal is stable.

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   Before changing from one product to another, i.e. to a product with a different part number, confirm that the change will not lead to problems.

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