Application Report

SNOA949 – May 2016

Power Reduction Techniques for the Multichannel LDCs in Inductive Sensing Applications

Rachel Liao

ABSTRACT

Inductive sensing is a contactless technique for applications ranging from position or motion measurement of a conductive target to detection of spring compression or extension. Depending on the specific application, there are different system requirements regarding sensitivity, responsiveness, and power. Power consumption is a key parameter for many applications, including wearables, consumer electronics, and some automotive applications. This application note covers techniques to reduce power consumption for TI's LDC1312, LDC1314, LDC1612, and LDC1614 inductive-to-digital converters and various experiments to verify the effectiveness of these power-reducing techniques.

Contents

Trademarks

1 Introduction

The multichannel LDC devices utilize an LC tank-based sensor to determine the change in inductance by measuring (sampling) the change in oscillation frequency of the sensor. The sensor oscillation frequency (f_{OSC}) is compared to an independent reference clock (f_{REF}) to produce an output sample that represents f_{OSC} as a fraction of f_{REF}. This fraction is represented as a digitized output code which then can be used to determine position or proximity of a moving conductive target. The power consumption of these LDC devices is typically on the order of a few milliamps when in continuous sampling mode. One of the advantages of inductive sensing technology over a competitive Hall effect sensor is that Hall effect sensors typically lack a low-power mode which would make it more difficult to decrease the power consumption when compared to the LDC sensing technology.

2 Duty Cycling

For low power applications, duty-cycling the LDC is a technique that can be used to reduce the power consumption. When the LDC can sample much faster than the application requires, the device can be put into a lower power mode while it is not in the data conversion process. The device is only active when it is performing a measurement conversion to minimize the total amount of current flowing through the device and therefore reduce overall power consumption. The LDC devices have two low power modes that can be used for duty-cycling. The first one is sleep mode where the LDC retains its registers contents except for those in the data registers. The second one is shutdown mode where the LDC loses all its register contents and the shutdown (SD) pin on the chip itself needs to be toggled. For consistency, the rest of this document will refer to sleep mode as the low power mode when discussing duty-cycling.

One of the main tradeoffs associated with this duty-cycling technique is responsiveness. The higher the sampling rate, the more responsive the system is, but at the cost of higher average power. Many applications do not need a fast response time and can benefit from the lower power consumption that comes with a lower sampling rate. For example, a human-machine interface (HMI) may only need a sampling rate of 20 SPS or lower, which is much lower than the peak 13 kSPS of the multichannel LDC devices. The total conversion time of a measurement for a given sampling rate can also affect power consumption depending on the resolution requirements. This concept corresponds to the duty cycle of the device at a particular sampling rate.

2.1 Operational Parameters That Affect Duty Cycling

The multi-channel LDC family of devices has 2 and 4 channel versions. When configured to sample on multiple channels, the LDC sequentially samples the channels. Figure 1 and Figure 2 show both single channel and multichannel mode sequencing in continuous conversion of the LDC, representing a non-duty cycled mode of operation. The normal sequence of tasks on each channel include sensor activation, conversion, channel switching (multi-mode only), and data readback.

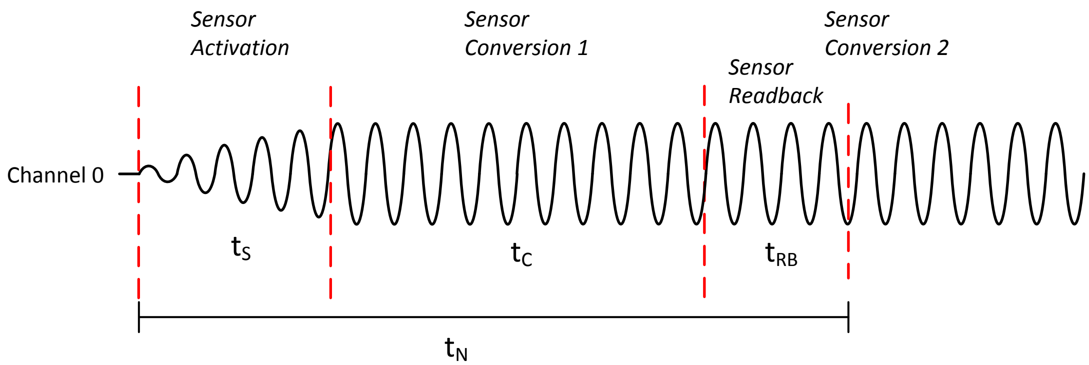

Figure 1. Single-Channel Mode Sequencing In Continuous Conversion

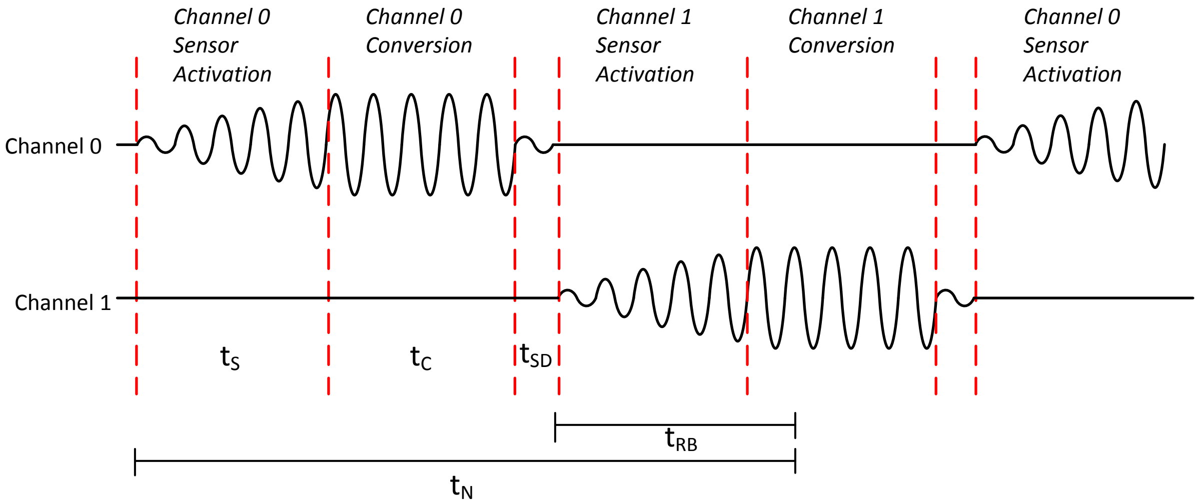

Figure 2. Multi-Channel Mode Sequencing In Continuous Conversion

The sum of the times it takes for each task to complete is equivalent to a sample time, during which the device needs to be actively running. In the data sheet this is referred to as normal mode. In the remainder of this applications note this will be referred to as *active mode*. We will also distinguish between sampling period (T_S) and sampling time (t_N). The former is defined as the time between consecutive samples on the same channel, and the latter is defined as the time required to obtain a single sample. This is expressed in Equation 1 where t_N is the time the device spends sampling in active mode.

$$t_N = t_S + t_C + t_{SD} + t_{RB}$$

where

- t_N is the time the device spends sampling in active mode
- t_S is the sampling time
- t_C is the conversion time
- t_{SD} is the switch-delay time
- t_{RB} is the data readback time (1)

In general, $t_{SD} < t_S << t_C$. Consequently, t_C has the most impact on sampling time and hence, duty cycle.

The sensor activation time, t_S, refers to the amount of time needed for the sensor oscillation to startup and stabilize. This activation time (t_S) is programmable via the SETTLECOUNT register for each channel and given by Equation 2.

$$t_s = \frac{16 \times \text{SETTLECOUNT}}{f_{REF}}$$

where

- f_{REF} is the reference clock frequency (2)

The sensor conversion time, t_C , is the largest part of this sequence. It represents the number of reference clock cycles (RCOUNT*16) used to perform a measurement conversion. As seen in Equation 3, the sensor conversion time can be set by the RCOUNT register value for each channel.

$$t_c = \frac{(16 \times \text{RCOUNT} + 4)}{f_{REF}} \quad (3)$$

The choice of RCOUNT value is driven by the resolution required by the application. If the required resolution is N bits, then Equation 4 can be used to calculate an initial value for RCOUNT:

$$\text{RCOUNT} = 2^{(N-3)} \quad (4)$$

See either section 7.3.2 of the LDC1614 data sheet (SNOSCY9) or other application notes (SNOA944, SNOA945) for a more thorough explanation of RCOUNT and sample resolution.

When the LDC is in multichannel mode, the channel switch delay needs to be included in the total sampling time. This is the delay time between the end of a sensor conversion on one channel and the beginning of sensor activation on a subsequent channel. This delay time is relatively minimal and is given by Equation 5:

$$t_{SD} = 692\ \text{ns} + \frac{5}{f_{REF}} \tag{5}$$

In addition to the time required to complete the three tasks discussed above, the microprocessor takes some time to read back the channel measurement. This data readback time, t_{RB}, is a function of the data resolution, the number of data registers being read, the number of clocking cycles to read or write to each register, and the I^2C data rate.

The total time to complete this sequence is the total amount of time for which the LDC must be in active mode (Equation 1). If f_S is the required sampling rate and T_S is the sampling period (T_S=1/f_S), the idea behind the duty-cycling technique is that the device is put into sleep mode when it is not operating in this data conversion process (T_{SLEEP}= T_S - t_N). Consequently, the percentage of time the LDC is in a low power sleep mode is given by Equation 6:

$$\frac{T_{SLEEP}}{T_S} \times 100\% = \left(1 - \frac{t_N}{T_S}\right) \times 100\% \tag{6}$$

To place the LDC in sleep mode, write the value 1 to the CONFIG.SLEEP_MODE_EN register field. While in sleep mode, the LDC retains its register contents except for those in the data registers, which must be read before the device is placed in sleep mode. To exit sleep mode, write the value 0 to the CONFIG.SLEEP_MODE_EN register field.

For more information on how to configure the multichannel LDCs, refer to either the LDC131x data sheet or the LDC161x data sheet.

In summary, given a minimum sampling rate required by the application, the duty cycle only needs to be large enough to meet the minimum resolution requirements of the application. Figure 3 illustrates this graphically.

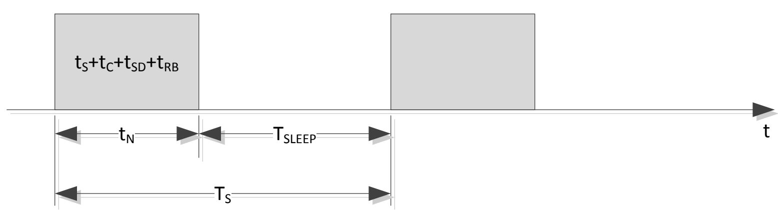

Figure 3. Duty Cycle as a Function of Settling Time, Conversion Time, Switching Time, and Readback Time

One other thing to note is that there is also a maximum limit to how fast the sampling rate can be while still allowing for duty-cycling. For example, if the application requires a high resolution where RCOUNT is 65535, then t_N is around 25 ms. In order for duty-cycling to work, T_S must be greater than t_N, otherwise T_{SLEEP} will be less than 0. Therefore, the sampling rate cannot be more than 40 SPS. Figure 4 shows the maximum sampling rate allowed for various RCOUNT values

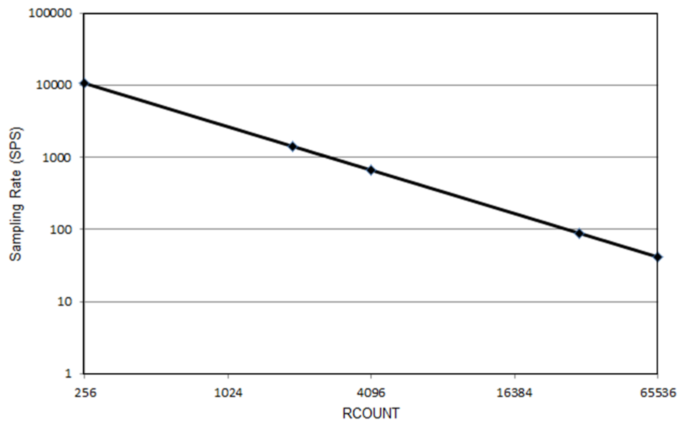

Figure 4. Maximum Achievable Sampling Rates for Various RCOUNT Values

3 Clock Gating

If an external oscillator is used, a second important technique in reducing the power consumption of the LDC is gating the external reference clock. Simply put, the reference clock is also put into a sleep state whenever the LDC is placed into a sleep state. This not only reduces the power consumed by the external clock, but also significantly reduces the leakage current from the LDC.

4 Test Setup

Duty-cycling the LDC was tested on the LDC1614 EVM with only one channel (Channel 0) enabled. The current flowing through the LDC1614 was measured using a Keysight (Agilent) 34410A digital multi-meter. The test setup is shown in Figure 5 and the testing conditions are given in Table 1.

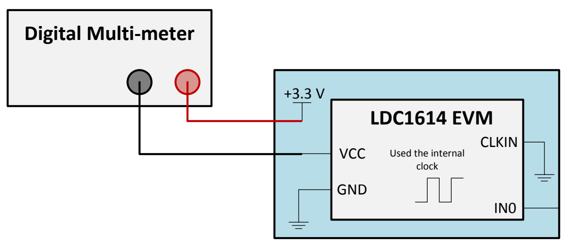

Figure 5. Test Setup

Table 1. Testing Conditions

	Channel 0
Internal Reference Frequency (MHz)	43.4
Sensor Frequency (MHz)	3.02
Amplitude (V_P)	1.27
Programmed SETTLECOUNT	32
Current Drive Setting (mA) (IDRIVE)	0.196

The reference frequency was set by the internal oscillator and the current drive was set to achieve the recommended voltage amplitude for the oscillation waveform, which is between 1.2 and 1.8 V_P.

5 Measurement Results

5.1 Measurements with Internal Clock

The LDC1614 EVM was programmed so that the LDC1614 was forced into the three different power modes: active, sleep, and shutdown. For each state, the current consumption of the device was measured and compared to the expected values given in the data sheet.

Table 2. Current Consumption For Each State: Internal Clock

	Measured Current (LDC1614 EVM)
Active Mode (10 MHz)	2.1 mA
Active Mode (43.4 MHz)	3.5 mA
Sleep Mode	35 µA
Shutdown Mode	0.164 µA

These supply current values are taken while using the internal reference clock. When using an external reference clock, it must be gated to achieve the current consumption specifications in the datasheet. If the external clock is not turned off while the LDC is in sleep or shutdown mode, the power consumption in these modes will be significantly higher. The clocking transitions result in an increase of the LDC input pin leakage currents, which is negligible when compared to the normal mode current, but is significant when added onto the lower power mode currents.

5.2 Current Consumption Measurements vs Data Conversion Time

5.2.1 Data Readback Overhead

The LDC1614 does not retain its conversion results when in sleep mode. Because of this, the device cannot be put into the sleep state until the channel conversion measurements have been read by the microcontroller. Therefore, the data registers must be read while the device is still running in active mode, which results in a fixed power consumption overhead. From the data given in Table 3, the data readback time is 0.688 ms if a 400-kHz I^2C interface is used. This overhead has a greater percentage impact on conversion times at low RCOUNT values where the data conversion times are less than 10x the data readback time.

Table 3. The Effect of Data Readback Overhead on Device Active Time

RCOUNT	Data Conversion Time (t_S+ t_C + t_{SD}) (ms)	Readback Time (t_{RB}) (ms)	Data Conversion Time + Data Readback Time (ms)
500	0.196	0.688	0.884
1000	0.381	0.688	1.069
5000	1.855	0.688	2.543
10000	3.699	0.688	4.387
20000	7.385	0.688	8.073
30000	11.072	0.688	11.76
40000	14.758	0.688	15.446
50000	18.445	0.688	19.133

5.2.2 Comparison of Measured and Estimated Current Consumption

5.2.2.1 Estimating Current Consumption

The following procedure can be used to estimate the current consumption of the LDC. First, the active time, or time the device spends in normal mode, should be determined. As expressed in Equation 1, this includes the sensor startup time, t_S, the sensor conversion time, t_C, and the data readback time, t_{RB}. The channel switch delay time, t_{SD}, can be ignored while operating in single channel mode. Once t_N has been calculated, the percentage of time the device spends in active mode, D_N, can be calculated using Equation 7 where T_S is the sampling period. The percentage of time the device spends in sleep mode, D_S, can also be calculated by using Equation 8.

$$D_N = \frac{t_N}{T_S} \tag{7}$$

$$D_S = \frac{(T_S - t_N)}{T_S} \tag{8}$$

Equation 9 then estimates the amount of power the LDC will burn given the above percentages per period (D_N and D_S) where I_N is the supply current in active mode and I_S is the supply current in sleep mode (given in Table 2).

$$I_{AVG} = D_N I_N + D_S I_S \tag{9}$$

5.2.3 Results

Figure 6 and Table 4 show the comparison between the experimental results and analytical results for varying values of RCOUNT.

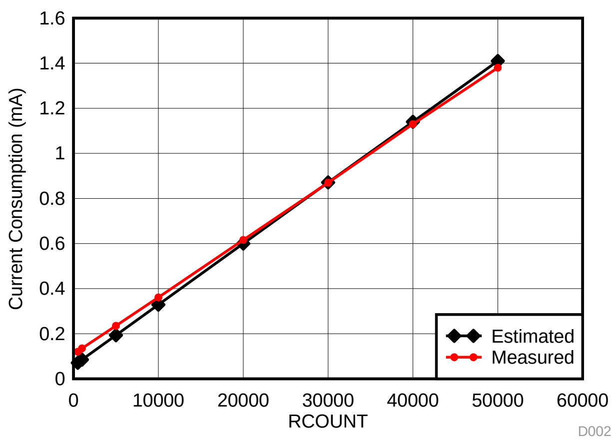

Figure 6. Comparison Between Measured and Estimated Current Consumption

Table 4. Differences in Measured and Estimated Current Consumption

RCOUNT	Duty Cycle	Measured Current, Active state (mA)	Estimated Current, Active state (mA)	Absolute Difference |Measured – Estimated| (mA)
500	0.42%	0.12	0.071	0.049
1000	0.82%	0.135	0.085	0.05
5000	4.02%	0.235	0.193	0.042
10000	8.02%	0.361	0.329	0.032
20000	16.02%	0.616	0.6	0.016
30000	24.02%	0.87	0.871	0.001
40000	32.02%	1.13	1.14	0.01
50000	40.02%	1.38	1.41	0.03

The above results show that the estimated current consumption is fairly accurate when compared to the measured current consumption – they differ only about an average of 30 µA. The estimated current consumption was calculated using TI's spreadsheet-based calculator tool, the Inductive Sensing Design Calculator Tool, which is based on the above equations and also takes into account other parameters such as the sensor frequency, sensor amplitude, and sensor current drive.

After verifying the current estimation model, a set of experiments varying RCOUNT values at different sampling rates were conducted duty-cycling with sleep mode and using the experimental setup shown previously in Figure 5.

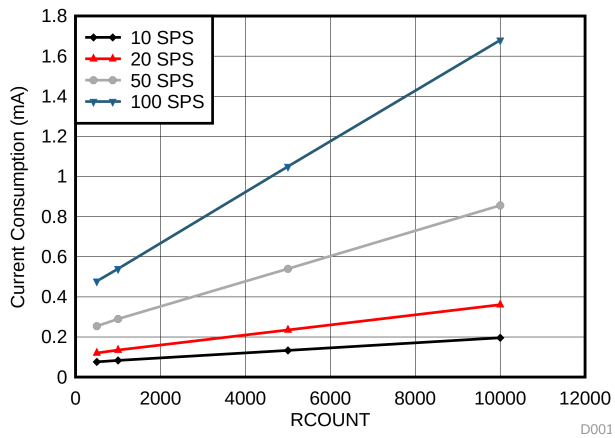

Figure 7. Current Consumption for Varying RCOUNT Values at Specified Sampling Rates

Figure 7 shows an approximately linear relationship between current consumption and RCOUNT. Since RCOUNT is directly related to sensor conversion time (Equation 3), a lower RCOUNT results in a shorter conversion time, t_C, and allows the device to spend less time actively running and more time in sleep mode (per sampling period, T_S). Therefore, for a given sampling rate, a lower RCOUNT consumes less current than a higher RCOUNT. Another way to understand this relationship is that if RCOUNT is kept constant but the sampling rate is varied, the LDC sampling at a higher rate consumes more power than a LDC sampling at a lower rate.

6 Summary

Duty-cycling and clock gating are effective techniques that can be implemented in order to minimize power consumption of the LDC1312, LDC1314, LDC1612, and LDC1614. In order to ensure that there is minimal current flowing through the device, systems using an external oscillator should turn off the oscillator while the LDC is not actively converting. Note that the data readback overhead can affect current consumption measurements, especially at lower RCOUNT values. The resulting current values for varying RCOUNT values at different sampling rates follow expected trends and the measured current values are similar to the estimated current values. The Inductive Sensing Design Calculator Tool provided by TI can be used as a reference tool for estimating the device power consumption.