Application Note

# Software/Hardware Design and Considerations for Zirconium Dioxide Oxygen Sensors

## 1. INTRODUCTION

This application note describes the recommended requirements in software and hardware to control, and analyse data from, SST Sensing’s range of zirconium dioxide oxygen sensors.

Before continuing a good understanding of application note AN0043 (which explains how our sensors work) is required.

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## 2. Amplifying and Sampling the Sensor's Sense Signal

### 2.1 Introduction

This section describes the hardware required to amplify the generated Nernst voltage from the sensor and also the ADC requirements to correctly sample the signal.

### 2.2 ADC Minimum Resolution

To accurately sample the sensor sense signal (Nernst Voltage) using the recommended hardware solution in Section 2.4 the ADC resolution must be at least 12bits. Two ADC channels are required as the signal is a differential signal (sense w.r.t common).

It is possible to use a single 10bit ADC but this involves two stage amplification to firstly amplify the signal then a second stage to remove the offset and scale the signal to use the entire 10 bit ADC input range. Due to the requirement for instrumentation amplifiers it is preferred to use higher resolution ADCs which are now common in most microprocessors and a lower cost amplifier setup.

### 2.3 ADC Acquisition Time

The acquisition time required to convert the analogue signal should be keep to a minimum. If the ADC is serviced by an interrupt it is important to keep its frequency equal to or greater than the maximum sample frequency (See Section 4.1).

### 2.4 Nernst Signal Amplification

The recommended circuit for amplifying the sensor Nernst voltage generated across the sense connection w.r.t the common connection is shown in Figure 001 on Page 3. The circuit provides two buffered and filtered outputs to be sampled by the ADC channels.

The key characteristics of the amplifier design are;

1. Good common mode noise rejection.
2. Biased for low frequency operation. The sense signal is typically less than 15Hz.
3. Op amp GBP of 10kHz ideal for low frequency operation.
4. Low input offset voltage ±150µV maximum.
5. Single ended power supply operation coupled with high PSRR (88dB typical).
6. Ultra low input bias current avoids loading of the sense signal.
7. Rail to rail input and output.
8. Low cost surface mount components used, X7R/X5R ceramic capacitors and 1% tolerance resistors.

### 2.5 ADC Averaging

To help reduce noise in the sampled signal the ADC results should be placed into a rolling average filter. (See Section 8)

It is recommended N should be between 16 and 32, when the ADC is sampled at 10KHz.

### 2.6 ADC Step Voltage

Knowing the step voltage is important when calculating the voltage level thresholds of the amplified Sense signal (See Figure 002).

To calculate the step voltage, Equation 001 should be used.

$$ADCStepVolts = \frac{Vs}{2^n} \quad \text{(Equation 001)}$$

Where:

ADCStepVolts= ADC Step Voltage
Vs = ADC Voltage Supply
n = ADC bit Resolution

<u>Example:</u>

For example if our ADC is connected to a 3.3V supply and the resolution is 12bits, then:

$$ADCStepVolts = \frac{3.3}{2^{12}} \quad \text{(Equation 002)}$$

The result gives us:

ADC Step Voltage = 0.00080566 Volts per bit.

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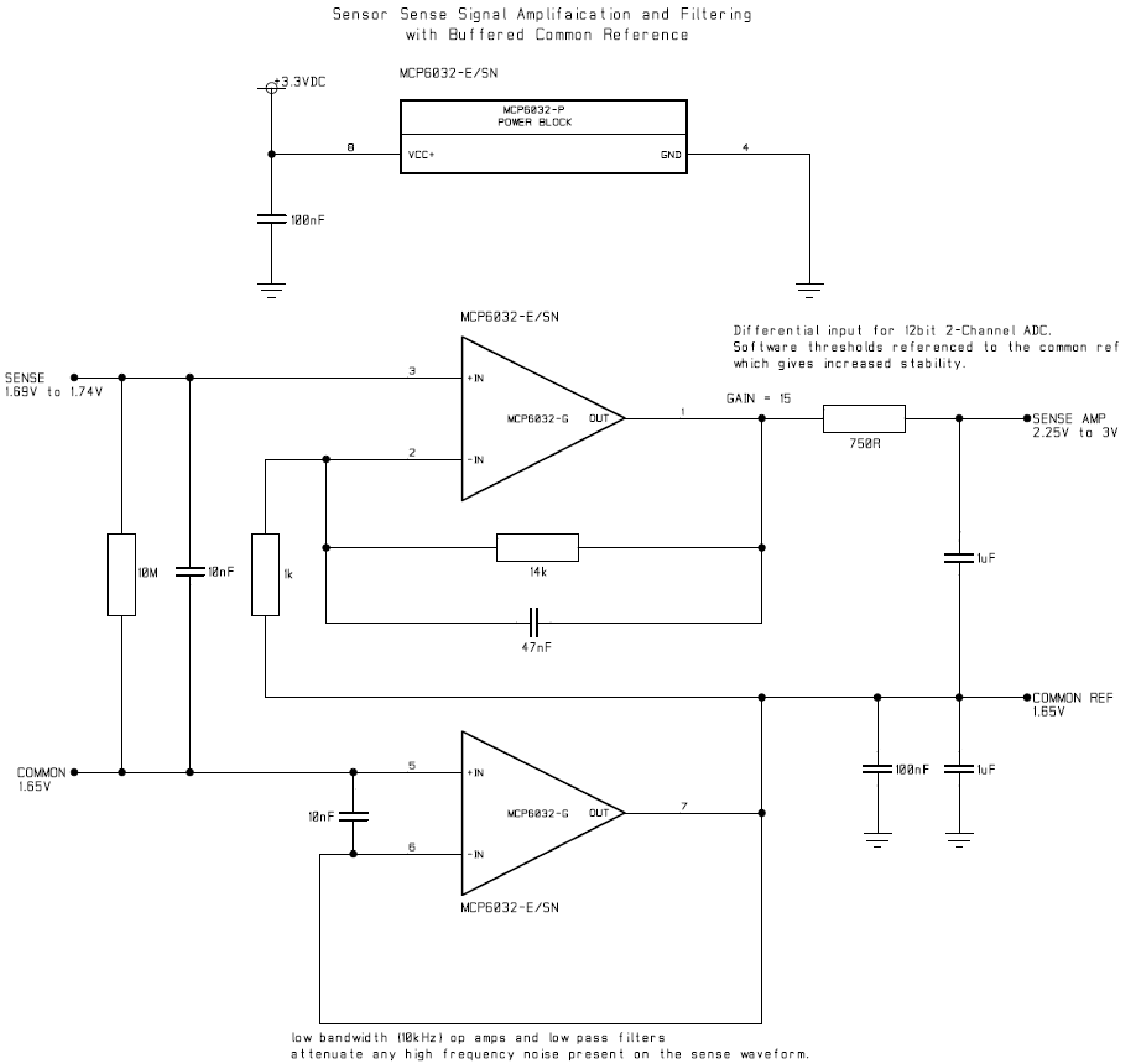


(Figure 001)

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## 3. Sensor Pump Control

### 3.1 Introduction

This section describes the relationship between the direction of the constant source supplied between the sensor pump and common connections and the generated Nernst voltage.

### 3.2 Pump Current Minimum Requirements (IMPORTANT!)

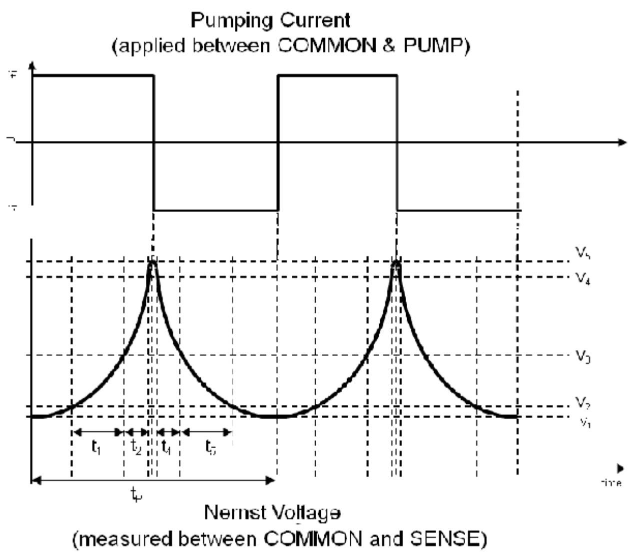
The minimum options required in software for controlling the direction of the pump current are;

- 40μA Pump to Common
- 40μA Common to Pump
- No Pump Current (sensor disabled)

It is important to have the capability to remove the pump current as this prevents the sensor being operated before the appropriate start routine is applied. Figure 002 shows the relationship between the applied pump current and the generated Nernst voltage.

Figure 004 on page 5 shows the recommended hardware to provide a true 40μA constant current source. This is very important for correct sensor operation. Note the voltage across the cell cannot exceed 1.65V as excess voltage will damage the sensor!

This simple constant current source uses a very low cost amplifier, X7R/X5R ceramic capacitors and 1% tolerance resistors. A digital output from the microprocessor connects to the terminal CCS reverse in the schematic.




(Figure 002)

### 3.3 Controlling the Waveform

To successfully run the sensor the pump current direction needs to alternated at fixed points V1 and V5 as illustrated in Figure 002.

To calculate V1 to V5 thresholds in software refer to Section 4.3.

The process for controlling the direction of the pump current is described in Figure 003.

When the sensor is first activated the 40μA pump to common must be applied to the sensor (CCS Low). It should remain in this state until the sampled sense voltage reaches the threshold V5.

The pump current direction can now be reversed and 40μA common to pump is applied to the sensor (CCS High) . The system should remain in this state until the sampled sense voltage reaches the threshold V1.

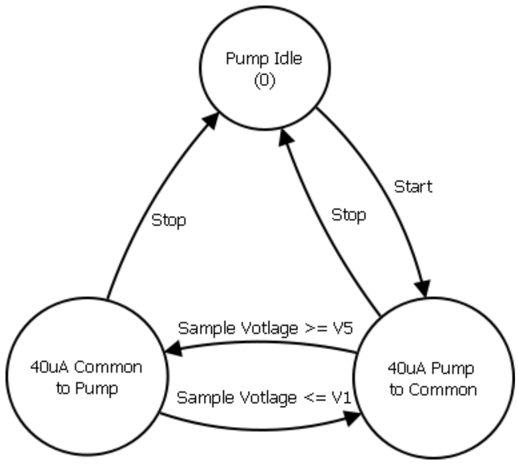
The system will continue to switch between states until the pump current is disabled (Pump Idle, CCS High Impedance or tri-stated) or power is removed from the microprocessor/ system.

### 3.4 Timeout Health Check (IMPORTANT!)

A pump current timeout should be introduced as a fault detector. This can help indicate a faulty sensor or a problem with the interface.

This can be achieved introducing a timeout of approximately 30 seconds. The timeout should be reset at each pump current reversal.

When a timeout occurs the stop routine should be implemented (See section 6).




(Figure 003)

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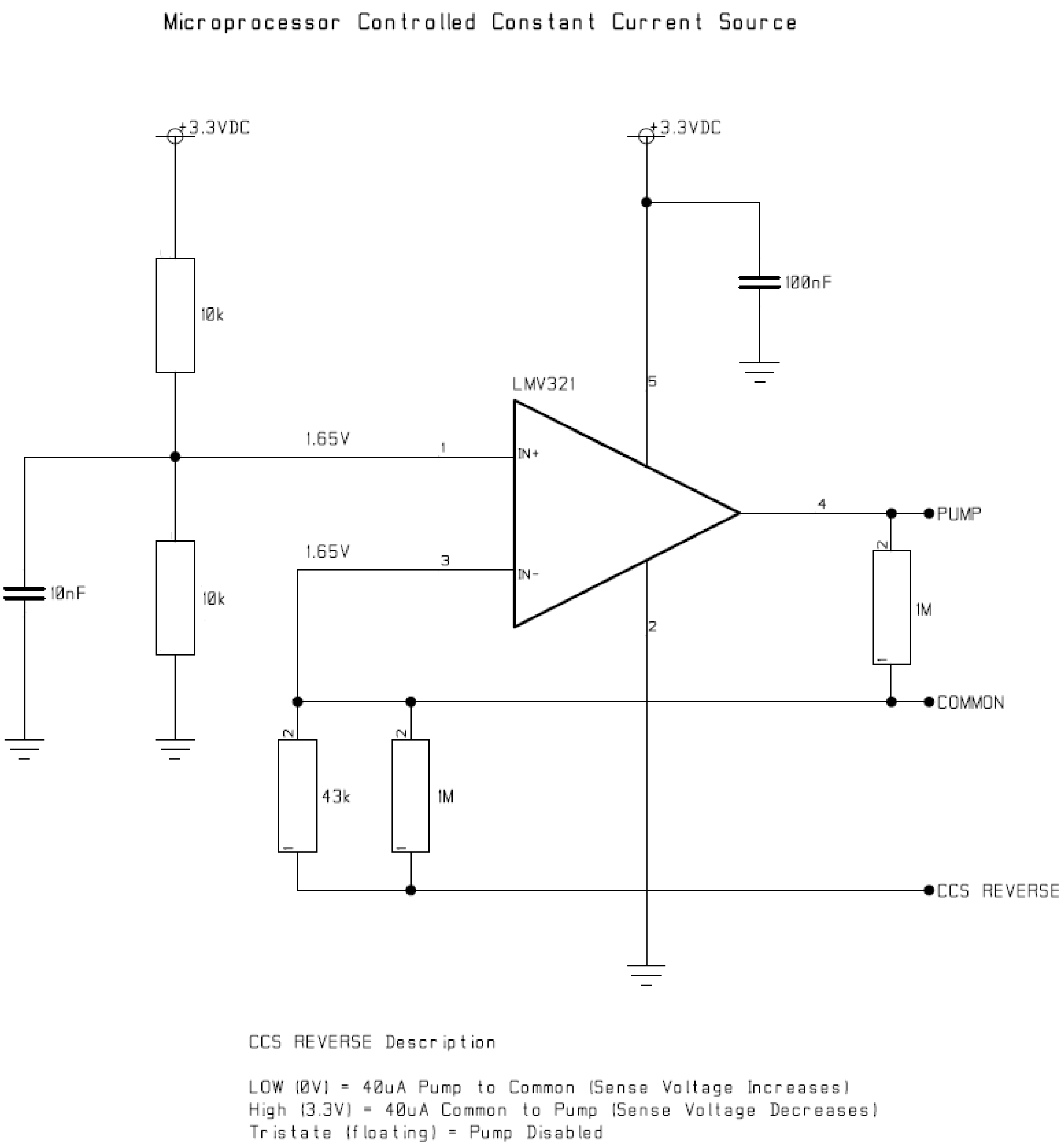


(Figure 004)



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## 4. Signal Processing

### 4.1 Sample Frequency

For the best possible accuracy a minimum sample frequency of 10kHz should be implemented in the system.

Higher frequencies up to 30kHz can be used to marginally increase accuracy but the benefits are minimal and not normally required for the majority of applications.

### 4.2 Timer Requirement

To sample the amplified sense signal correctly a timer is required to be set up to measure T1, T2, T4 and T5.

If an interrupt timer is used it is important to make sure a high priority is assigned to the interrupt to prevent inaccurate measurements.

The time resolution needed has to be equal to or greater than the chosen sample frequency, although it should be noted that having greater time resolution will yield no extra benefits.

Example:

If using a 10kHz sample frequency the a time resolution of 0.1ms will be sufficient.

### 4.3 Voltage Level Calculations

To calculate the sense voltage levels (V1 to V5) correctly a good understanding of the sense amplification and the ADC Step Volts (Section 2.6) are required.

Taking into account all amplification gains (x15 for the recommended circuit) and the common reference voltage (if applicable) the following equation should be used to calculate each threshold in ADC steps;

$$Threshold = \frac{Vsense - Vcommon}{ADCStepVolts} \qquad \text{(Equation 003)}$$

Where:

Threshold = Digital Threshold Voltage level (ADC Steps)
Vsense = Each amplified sense voltage, V1 to V5 (SENSE AMP from figure 001)
Vcommon = Common reference voltage (COMMON REF from figure 001)
ADC Step volts = ADC Volts per step as calculated in Section 2.6.

The calculated thresholds in ADC steps can be saved in a lookup table for system reference.

The recommended Nernst voltages at the sensor level vs the corresponding ADC thresholds for 12bit ADCs using the recommended circuit from Figure 001 can be found in Table 001 on Page 7.

The system should sample both ADC channels applying the rolling average described in Section 2.5 and Section 8. Every measurement should be Vsense minus Vcommon and this result should be compared to the ADC thresholds in Table 001.



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| Thresholds | Nernst Voltage at the sensor | 12bit ADC Threshold (Amplified Sense - Common) |
|---|---|---|
| V1 | 40mV | 745 |
| V2 | 45mV | 838 |
| V3 | 64mV | 1191 |
| V4 | 85mV | 1583 |
| V5 | 90mV | 1676 |

(Table 001)

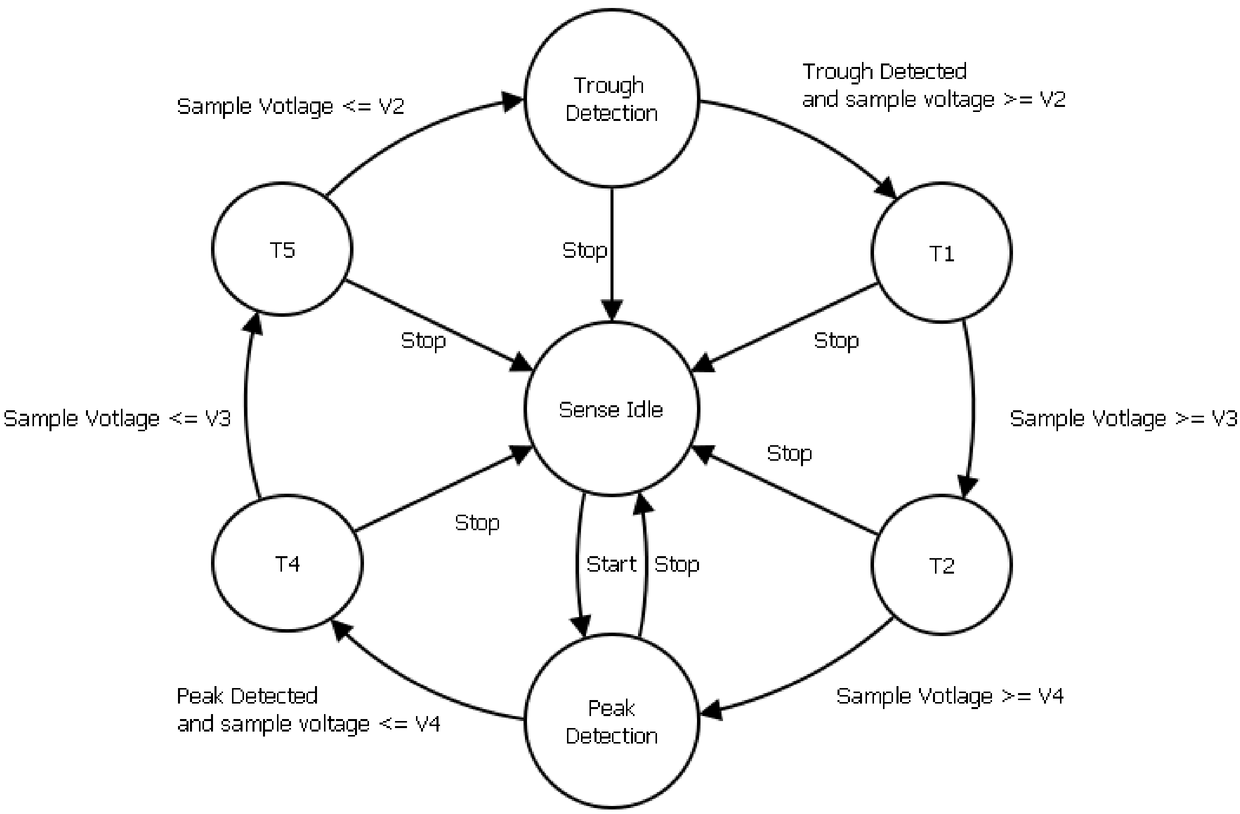


Figure 005

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## 4. Signal Processing (Cont.)

### 4.4 Signal Sampling

To illustrate the sampling of the sense signal the waveform can be split up into six unique steps. Figure 005 on the previous page and the following steps describe the process and operations required.

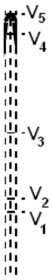
Individually each step has it own process to perform in order to obtain the timing values (T1, T2, T4 and T5) required to calculate Td and subsequently %O2.

**Idle State**

Current Direction: No Pump Current

In Idle state the system should not be trying to sample the Sense signal. Once the sensor pump current is activated the system should begin at Step One: Peak Detection. The pump current should always initialise in the state 40µA Pump to Common.

**Step One: Peak Detection**

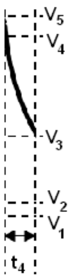



*Current Direction: 40µA Pump to Common -> 40µA Common to Pump*

In this section the system should be looking to detect the first peak when the sampled Sense voltage is >= V5. When this occurs the pump current should be reversed as described above.

Once the sampled Sense voltage is <= V4, Step Two: T4 is activated.

**Step Two : T4**

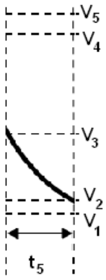



*Current Direction: 40µA Common to Pump*

When entering this section the timer should be initialised/reset. This is done when the sampled Sense voltage is <= V4.

Once the sampled Sense voltage is <= V3, the results from the timer can be stored as T4. Step Three: T5 is now activated.

**Step Three : T5**

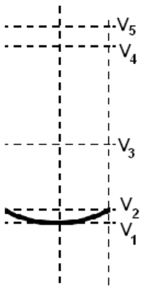



*Current Direction: 40µA Common to Pump*

When entering this section the timer should be reset. This is done when the sampled Sense voltage is <= V3.

Once the sampled Sense voltage is <= V2, the results from the timer can be stored as T5. Step Four: Trough Detection is now activated.

**Step Four : Trough Detection**

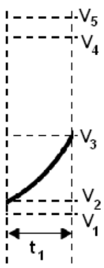



*Current Direction: 40µA Common to Pump -> 40µA Pump to Common*

In this section the system should be looking to detect the waveform trough when the sampled Sense voltage is <= V1. When this occurs the pump current should be reversed as described above.

Once the sampled Sense voltage is >= V2, Step Five: T1 is activated.

**Step Five : T1**

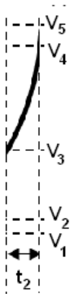



*Current Direction: 40µA Pump to Common*

When entering this section the timer should be reset. This is done when the sampled Sense voltage is >= V2.

Once the sampled Sense voltage is >= V3, the results from the timer can be stored as T1. Step Six: T2 is now activated.

**Step Six : T2**




*Current Direction: 40µA Pump to Common*

When entering this section the timer should be reset. This is done when the sampled Sense voltage is >= V3.

Once the sampled Sense voltage is >= V4, the results from the timer can be stored as T2. Step One: Peak Detection is now activated and the continuous loop begins again.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## 5. Start Routine

### 5.1 Introduction

The start routine is required every time the sensor is switched off or power cycled. This helps prevent irreversible damage to the oxygen sensor which can occur if the sensor is pumped when the zirconium dioxide sensing cell is cold.

On system initialisation it is important to make sure the pump current and signal processing are deactivated.

The start routine is illustrated in Figure 006.

### 5.2 Start Routine Description

The first process should be to make sure the heater is enabled to heat up the sensor. After the heater is applied the system should then begin a warm up delay period with a minimum of 60 seconds.

On delay completion the pump current and signal processing can be activated to allow the sensor to begin its pump cycle.

The following stop routine should be applied to shutdown the sensor operation correctly.

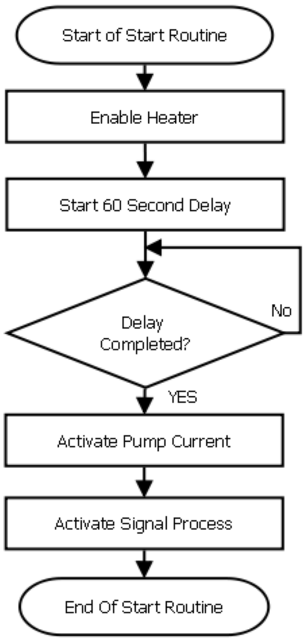


Figure 006

## 6. Stop Routine

### 6.1 Introduction

Some applications may require the sensor to be stopped during operation for safety, maintenance or for energy efficiency reasons.

The correct stop routine is illustrated in Figure 007.

### 6.2 Stop Routine Description

The first process should be to deactivate the pump current and signal processing. Minimal delay should be present between each process shutdown. The heater may then be turned off.

The system cool down delay is a optional process depending on the application requirements. If used a minimum of three minutes should be applied. It may be necessary for a longer delay to be implemented to allow the application to fully cool down before the sensor heater is turned off. The delay should be determined by the application and it’s purpose is to prevent condensation forming on the sensor in humid environments during the shutdown process.

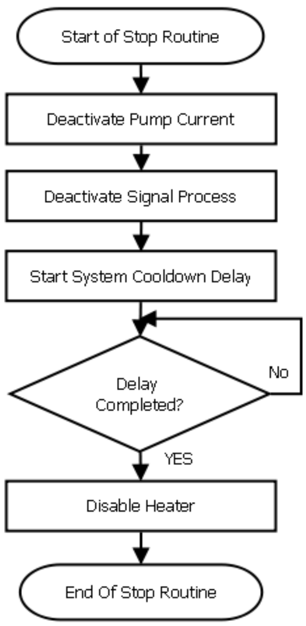


Figure 007

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## 7. Calculations

### 7.1 Introduction

The calculations needed to calculate Td and for diagnostics are not time dependant and can be managed during the processors free time.

Tp is time dependant and will need to be calculated using a timer which is reset at each peak or trough detection.

### 7.1 Td

The following equation is used to calculate Td;

$$Td = (T1 - T2) + (T5 - T4) \qquad \text{(Equation 004)}$$

The time values (T1, T2, T4 and T5) are obtained during the signal processing routine. Therefore Td only needs to recalculated after every new T value.

It is recommended Td is put into a rolling average filter to reduce noise and stabilise the Td output. We recommend a buffer size of between 4 to 400. This value is very application dependant with a small buffer size best for fast sensor response and a large buffer size optimal for output stability.

Therefore the maximum buffer size is ideal for systems with slowly drifting O2 levels and the minimum buffer size is ideal for applications with rapidly changing O2 levels.

For a balance between response and stability a buffer size of 100 is ideal.

For applications where both response and stability are critical an adaptive filtering method may be used. This can be achieved by monitoring the variance in each new recorded Td value and when the variance exceeds a predetermined level the buffer is flushed and the buffer size reduced to its minimum value. When the Td values begin to stabilise again the buffer size can be gradually increased until it reaches its maximum value.

### 7.2 Tp

The Tp calculation can be made by measuring the period of the sampled Sense voltage waveform. The recommended way to perform this calculation is to measure the time between the waveform peak to peak as this generally more repeatable than measuring the time between the trough to trough.

The frequency of the signal can also be calculated using Equation 005. Tp should be non zero before this calculation is made.

$$Freq = \frac{1}{Tp} \qquad \text{(Equation 005)}$$

### 7.3 Asymmetry

The equation for calculating the sampled Sense voltage asymmetry is displayed in Equation 006.

$$Asymmetry = \frac{(T1 + T2)}{(T5 + T4)} \qquad \text{(Equation 006)}$$

Asymmetry need only be recalculated on each new T value at the same time as Td.

To help avoid divide by zero fault conditions during the start-up cycle it is good practice to only calculate asymmetry if T4 or T5 are not equal to zero.

The asymmetry value should also be placed into a rolling average filter to reduce noise and add stability. A buffer size of 10 to 100 is recommended.

### 7.4 O2

To transform the calculated and buffered Td values into the corresponding O2% in the atmosphere a calibration scalar (Cs) is required (See section 9).

The O2% value can then be obtained using Equation 007.

$$O2 = TD(Ave) \times Cs \qquad \text{(Equation 007)}$$

It should be noted that this is an averaged O2 value as the buffered Td value is used in the calculation.

If an instantaneous O2 value is required then Td (Ave) can be replaced with each newly calculated Td. This is often referred to Td raw and the calculated oxygen level as O2% raw.

If using a barometric pressure sensor to compensate for pressure changes please refer to Section 4.5 of AN0043 for guidance.



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## 8. Rolling Average Filter

### 8.1 Filter principle

A basic rolling average filter is defined as the sum of all the last N number of data points divided by the number of results. See Equation 008.

$$Average = \frac{x_1 + x_2 + \dots + x_{N-1} + x_N}{N} \quad \text{(Equation 008)}$$

Where:

N = Buffer size
X = Data

This simple filter is extremely useful in reducing noise in a signal or system. It can also be quickly implemented into a system to improve the stability of sampled signals.

### 8.2 Processor Overhead

In some applications this approach can be problematic depending on the platform and compiler. The process of division can take a large amount of processing power and therefore time.

As the measurement of oxygen in this system is very time dependant all efforts should be made to avoid any unnecessary overheads.

One option to reduce the overhead is by replacing the intensive division calculations present in the averaging filters, with a less intensive process.

A division of two can be easily implemented by shifting the value right by one.

<u>Example:</u>

Binary: 00001000 which equals decimal value 8.

becomes:

Binary: 00000100 which equals decimal value 4.

Using this principle we can carefully select N such that it equates to 2 to the power of y. See Equation 009.

$$N = 2^y \quad \text{(Equation 009)}$$

Where:

N = Chosen Buffer Size
y = Number of places to shift to the right

## 9. Calibration Considerations

To calculate the calibration scalar used in Section 7.4, Equation 010 should be used:

$$Cs = \frac{O2Per}{Td} \quad \text{(Equation 010)}$$

Where:

Cs = Calibration Scalar.
O2Per = Known O2 Percentage in the calibration environment.
Td = Average Td value.

Before a calibration process it is vital to make sure the sensor output is stable and the environment only comprises of the calibration gas. It is for these reasons that the sensor is normally calibrated in normal air to 20.7% O2 and the sensor is given 10 minutes after powering the heater before proceeding with calibration.

If the heater has been on for more than ten minutes then the sensor only requires 5 minutes in the calibration gas before a calibration can proceed.

If a calibration gas of another known oxygen concentration is available then this may be used by replacing O2Per in the equation above.

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| WARNING | CAUTION |
|---|---|
| **Personal Injury**<br>DO NOT USE these products as safety or Emergency Stop devices or in any other application where failure of the product could result in personal injury.<br>**Failure to comply with these instructions could result in death or serious injury.** | Do not exceed maximum ratings and ensure the sensor is operated in accordance with all requirements of AN0043.<br>**Failure to comply with these instructions may result in product damage.**<br><br>**It is the customer's responsibility to ensure that this product is suitable for use in their application. For techincal assistance or advice, please email us: technical@sstsensing.com** |

**General Note:** SST Sensing Ltd reserves the right to make changes in product specifications without notice or liability. All information is subject to SST's own data and considered accurate at time of going to print.



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