Application Report

Synchronized Measurements with Digital Current Sense Monitors

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ABSTRACT

It is a common hardware requirement for multiple analog-to-digital converters to sample simultaneously. As digital current sense monitors are analog-to-digital converters with front end circuitry specific to current sense applications, it follows that some use cases may need to have synchronized measurements between different digital current sense monitors. This application note presents a methodology for synchronizing measurements between digital current sense monitors. Results are presented for synchronized measurements among four INA233 devices.

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1 Introduction

At a high level, digital current sense monitors (also called digital power monitors) consist of an analog front end that is designed to take differential measurements across a sense resistor at a high common mode voltage, an internal analog to digital converter, and a digital output to provide the measurement data to the rest of the system. I^2C digital current sense monitors, such as the INA233 (Figure 1-1), offer one shot measurement capabilities which allow the I^2C controller (main) to tell the current sense monitor (secondary) to initiate a single measurement. Since traditional I^2C communication exists between one main and one addressable secondary on the I^2C bus, it is not possible for a single main to initiate a synchronized one shot measurement for multiple secondary devices. However there could be exceptions where commands are provided specifically for this function.

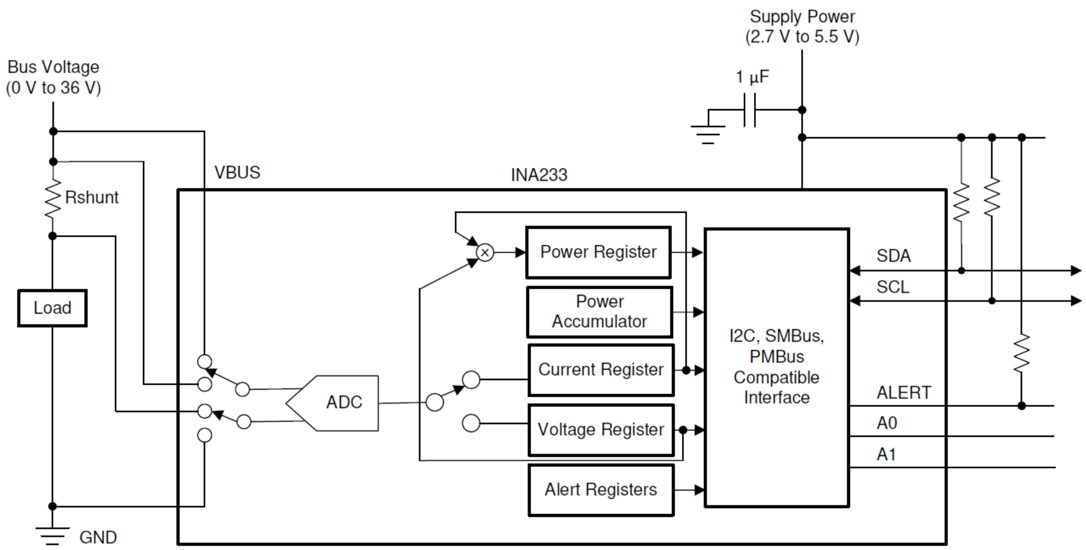

Figure 1-1. INA233 Block Diagram

The Power Management Bus (PMBus) is a variation of the System Management Bus (SMBus) which was created for controlling power devices with digital interfaces. Both PMBus and SMBus are based on two-wire open-drain electrical signaling like I^2C , but have additional application- specific features. In the case of desiring synchronized measurements between or across multiple digital current sense monitors, a group command exists within PMBus that allows the main to address multiple secondaries sequentially, but execute the command at the same point in time.

2 Group Command Details

INA233 supports group protocol as defined in the PMBus specification. The group command allows the host processor to easily communicate with multiple devices on the bus. Commands are sent in one continuous transmission, and the STOP condition at the end serves as the “go” command. Upon detection of the STOP condition, all devices begin executing the received command. During the transmission, each device can receive only one command, and the commands don’t have to be identical for all devices.

The INA233 also supports packet error checking (PEC). PEC is an optional feature which can help improve communication robustness. In this study, communication protocol was implemented without PEC.

The format of group protocol is shown in Figure 2-1. In this study, the one-shot (or triggered) conversion command is transmitted to each of the INA233 serially by writing to the MFR_ADC_CONFIG register. Repeated START conditions are used to separate the devices from each other.

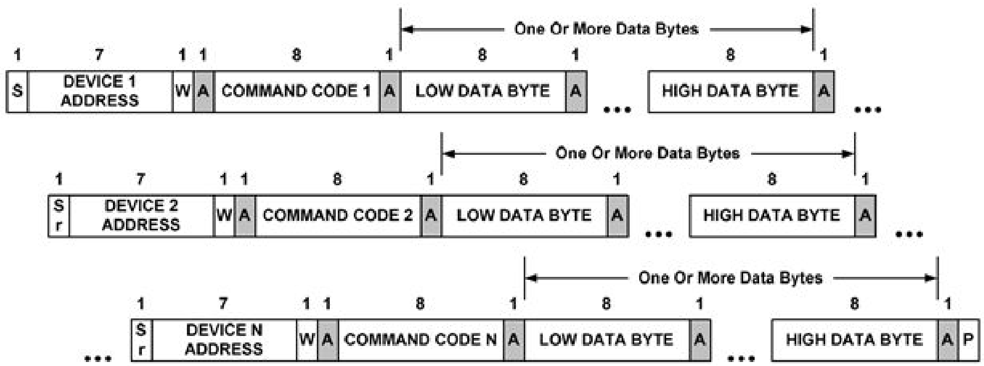

Figure 2-1. PMBus Group Command Protocol without PEC

For each device, the command is identical in format to a normal write word, except no STOP condition is generated unless the last device has been addressed and the end of the transmission has been reached. Figure 2-2 shows the write word command. The STOP condition (highlighted) at the end should be omitted unless the transmission is targeting the very last device in the group.

As we can see from Figure 2-2, four bytes of data are sent to each member within the group. The first byte is the unique device address; the second byte is the command code. In this study, the command code is D0h, or register MFR_ADC_CONFIG. It is followed by two bytes of data with mode bits (bit2 to bit0) set to “001”. This instructs the INA233 to start converting shunt voltage in triggered mode upon receiving the command.

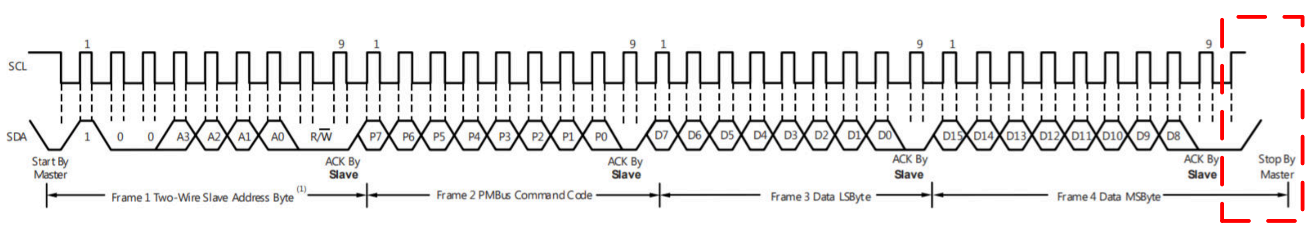

Figure 2-2. INA233 Write Word

Results are presented in this application report for the INA233, but the PMBus group command functionality is applicable to other TI devices that support PMBus.

3 Bench Setup and Group Command Verification

Figure 3-1 shows the bench configuration that is used to verify that the PMBus group command can synchronize measurements among four INA233 devices. *Vdiff* is the input shunt voltage source and is time varying; *Vcm* is the common mode input voltage source and is set to 0*V*. Each INA233 is assigned a unique address and all four are connected in parallel to sample the same input source.

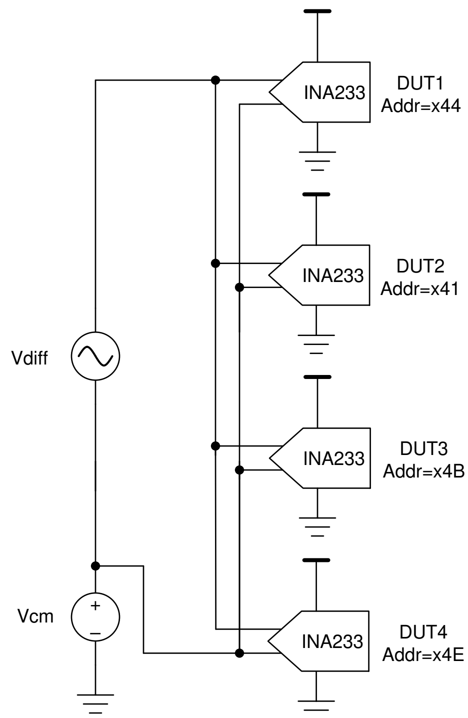

Figure 3-1. Bench Set-Up with Four INA233 Devices

In order to verify that the group command is synchronized, it makes sense to monitor when the ADC channels begin their conversions. However, there is no external indicator of the ADC conversion start that is available at the board level. In lieu of this, the best external indicator of synchronized conversions is the Conversion Ready signal, which can be brought out through the ALERT pin via setting the MFR_ALERT_MASK register. Therefore, the toggling of the ALERT pin will be used as an indicator of this functionality.

Note that potential differences in parasitic loading on the ALERT pins of the individual devices may impact the response timing. Also note that due to inherent variation in the device's internal oscillator frequency, variation in the ALERT signals is expected (as shown in Figure 3-2 for a 8.2*ms* conversion case and Figure 3-3 for a 140*us* conversion case). Due to the cumulative effect of this variation over time, oscillator frequency variation leads to greater differences in completion time for longer conversions. Larger averaging number requires longer total conversion time, therefore similar greater difference in completion time can be expected as well.

Figure 3-2. ALERT Signals with 8.2*ms* Conversion

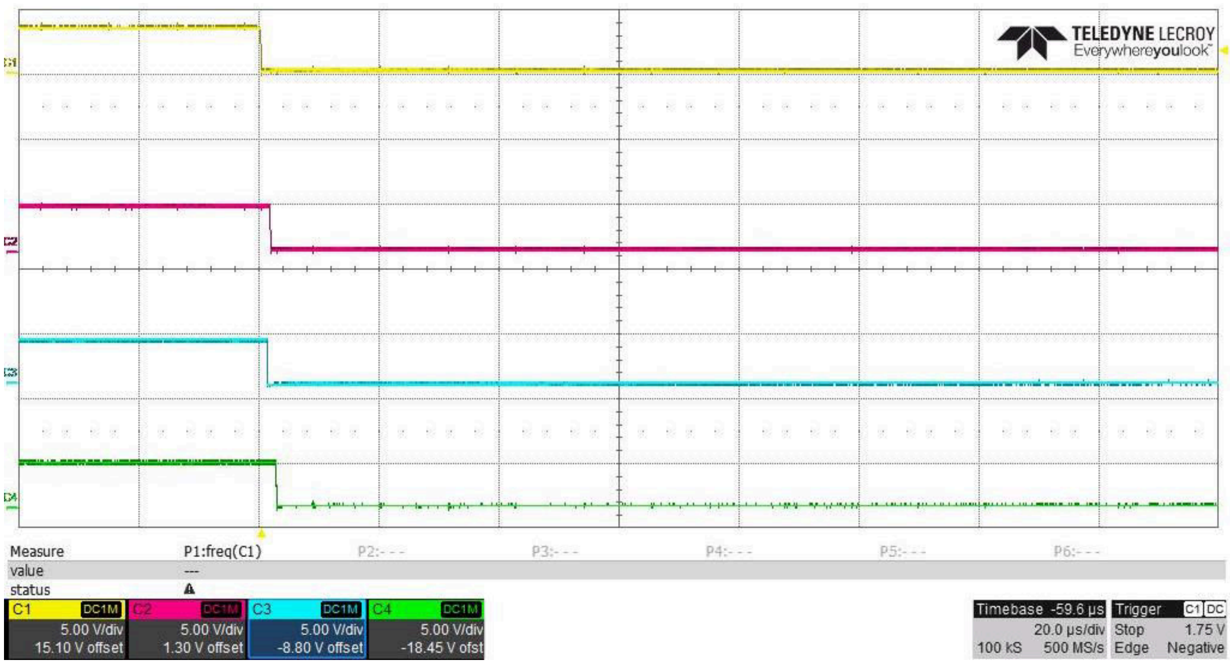

Figure 3-3. ALERT Signals with 140*us* Conversion

Another factor that affects the conversion completion time is the uncertainty in start time, because the internal system clock is not synchronized among descrete devices even if they are perfectly matched. This effect is best demonstrated with a persistent plot, where the conversion time is set to the shortest, as shown in Figure 3-4.

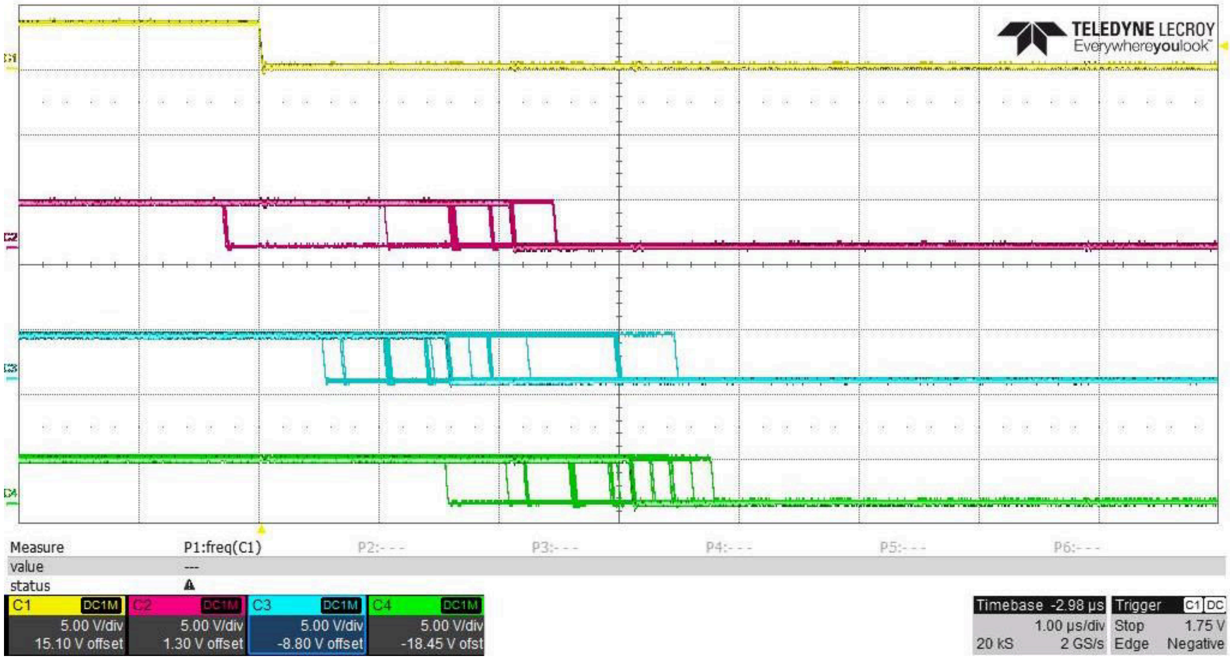

Figure 3-4. Persistent Plot of ALERT Signals

PMBus group command protocol requires all devices to execute their individual commands only upon receiving the STOP condition. Therefore, the order in which the devices in the group are addressed should have no effect on command execution order. Additional testing was completed to verify and show that there is no sequential relationship between the order the devices are addressed and the order of the ALERT signals. The variation in the timing of the ALERT signals comes only from the inherent variation of the internal oscillator frequency. Compare Figure 3-5 and Figure 3-6 below.

In Figure 3-5, the INA233 devices are addressed serially in the order of 1 through 4 (i.e. 1-2-3-4). ALERT pins are monitored for devices 1 and 4 as indicators of conversion complete. In Figure 3-6 the positions of devices 1 and 4 are swapped, and the addressing order becomes 4-2-3-1. Again, the ALERT pins are monitored for devices 1 and 4. Notice the relative position of the ALERT signal remains unchanged.

Figure 3-5. Addressing Order: 1, 2, 3, 4

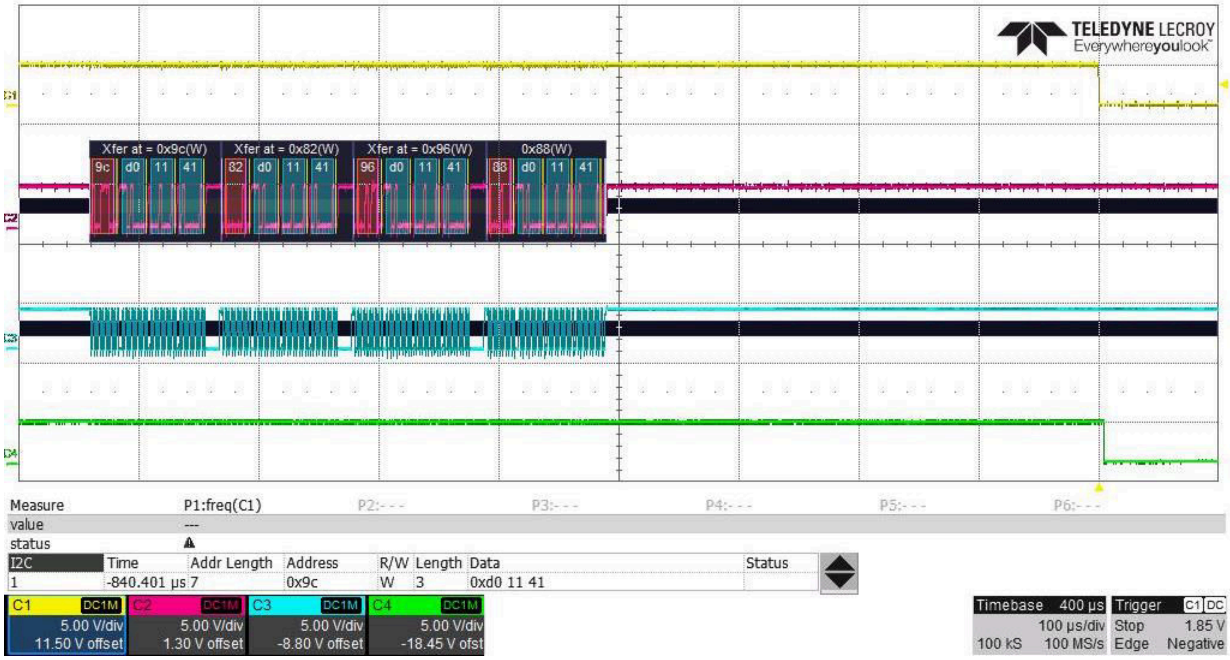

Figure 3-6. Addressing Order: 4, 2, 3, 1

Additional testing was completed to verify the robustness of the group command. In this experiment, large time delays were inserted in the addressing sequence of the devices on purpose; it is shown that these delays do not impact the synchronized behavior of the device. Figure 3-7 shows 1*ms* delays in the addressing sequence of the devices and Figure 3-8 shows the same 1*ms* delays with a changed addressing sequence. Both test set-ups result in synchronized measurements, with the variation in ALERT signals deterministically following each device as a result only of internal oscillator variation.

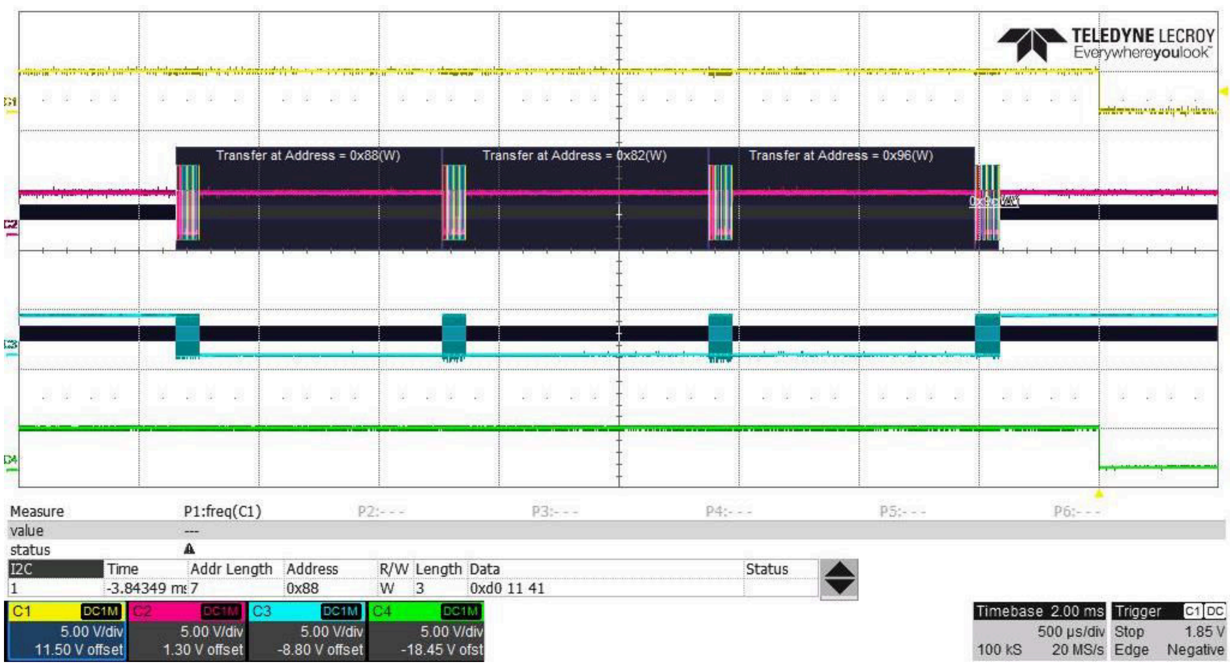

Figure 3-7. Large Delay and Addressing Order: 1, 2, 3, 4

Figure 3-8. Large Delay and Addressing Order: 4, 2, 3, 1

The combination of the above results from the group command verification show that it is possible to execute synchronized measurements between multiple INA233 devices with a single command from the controller.

4 Measurement Results and Trade-Offs

Measurements were performed with a 100*Hz*, ± 100*mV* triangle wave (Figure 4-1) applied to all four INA233 devices. The Group Command is issued to trigger a synchronized one-shot ADC conversion with no averaging. Each INA233 reports back its conversion result in subsequent separate READ transactions. Therefore each time such a conversion-read loop is executed, we get a set of data consisting of four measurements, one from each INA233. This process is repeated several hundred times for each conversion time setting while the AC input is free running. Because the INA233 shunt voltage input range is ± 81.92*mV*, in a set of measurements, if any one or more are outside of INA233 input range, the set is discarded and not included in the statistics. Within each set of four measurements, the mismatch is defined and calculated as the difference between the largest and smallest measurements. When all mismatch data for a conversion time setting are aggregated, the min, max, standard deviation and average can be calculated.

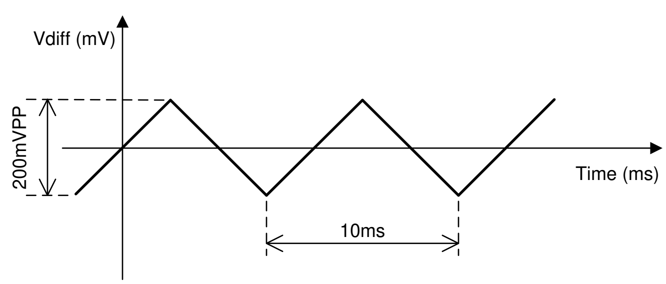

Figure 4-1. Differential Input Signal

The results are presented in Table 4-1. Note that the mismatch is mainly affected by timing, but also by other error sources including noise and input offset. These effects are not dominant and can't be distinguished. It is evident from the table that the measurements get worse with longer conversion time. While this might be counter intuitive for a DC input, it makes perfect sense for AC input of large amplitude. As shown in Figures 5 and 6, the mismatch in conversion time gets larger when conversion time gets longer. This larger time mismatch translates into larger measurement mismatch.

Table 4-1. Mismatch(*uV*) vs. Conversion Time with Large Input

Measurement mismatch(*uV*) vs. Conversion(single, no averaging) time								
	140*us*	280*us*	322*us*	588*us*	1.1*ms*	2.116*ms*	4.156*ms*	8.224*ms*
Min	8	13	25	73	198	20	10	5
Max	130	132	163	218	350	605	1128	1575
Stdev	30	26	31	35	36	149	338	455
Mean	66	71	87	145	274	451	735	823

INA233 offers programmable averaging modes as well as programmable conversion times. These features allow the device to be configured to optimize the available timing and precision requirements in a given application. Averaging is similar in effect to a longer conversion time. Therefore we can predict that for the same conversion time, as the number of averages increases, the measurement mismatch should get worse. To verify this, we selected a conversion time equal to 140***us*** and compared averaging of 16x and 128x. The relationship between measurement mismatch and averaging is presented in Table 4-2. As predicted, measurement mismatch increases with larger averaging periods.

Table 4-2. Mismatch(*uV*) vs. Averaging

Measurement mismatch(*uV*) vs. number of averaging (140*us* conversion)		
	16X	128X
Min	8	15
Max	75	1278
Stdev	164	391
Mean	449	772

In many applications, the load current to be measured results in a shunt voltage range which is much smaller than the input full-scale range of the device. To visualize how the INA233 performs in synchronized measurement of an AC input with low amplitude, we repeated the same tests with a 100*Hz*, ±2.5*mV* triangle wave. This input is also representative of a DC input superimposed with a low amplitude AC component. The relationship between measurement mismatch and conversion time is presented in Table 4-3. A lower amplitude input signal yields smaller mismatch, and thus longer conversion times can be used without a significant increase in mismatch as was seen for the ±100*mV* case.

Table 4-3. Mismatch(*uV*) vs. Conversion Time with Small Input

Measurement mismatch(*uV*) vs. Conversion(single, no averaging) time								
	140*us*	280*us*	322*us*	588*us*	1.1*ms*	2.116*ms*	4.156*ms*	8.224*ms*
Min	5	3	5	3	0	5	5	5
Max	65	55	40	28	33	33	43	50
Stdev	10	9	6	4	5	8	11	13
Mean	31	30	18	16	15	17	21	23

5 Conclusions

This application note presented a measurement methodology for synchronizing measurements between multiple PMBus digital current sense monitors. The use case of synchronized measurements between four INA233 devices was verified and examined in detail. Upon receiving the group command, all INA233 devices trigger at the same time, with some expected variation due to inherent variation in the internal oscillator frequency of each respective device. Addressing order has no effect on the INA233 conversion sequence or timing. Added delay between addresses during the group command has no effect on the INA233 conversion sequence or timing.

Measurement results for a 100*Hz* ±100*mV* triangle wave input signal showed that longer conversion time and/or averaging introduced larger measurement mismatch. Thus, for higher amplitude signals, a fast conversion time (for example, 140*us*) is recommended. Measurement results for a 100*Hz* ±2.5*mV* triangle wave input signal showed smaller measurement mismatch. Thus, for lower amplitude signals, longer conversion times can be used without a significant increase in mismatch.

Symmetrical AC input signals are used as test source in this study, however the findings are equally applicable to a DC voltage with a low amplitude AC component which is representative of many power supply applications.

6 Appendix - Group Command Pseudo Code

The following is the pseudo code used in this report:

```
//One time setup
INA233 Initialization
{
    //D0h  MFR_ADC_CONFIG - triggered or continuous; Shunt and/or Bus
    Configure ADC (averaging, conversion time, mode = triggered)
    //D4h MFR_CALIBRATION
    Program Calibration
    //Other one-time setup as needed
    ...
}

main
{
    INA233 ConversionGroupCmdTriggered
    {
        i=0;
        While(i<NumberOfINA233)
        {
            send START Condition;
            send SlaveAddress[i] + W bit;
            send MFR_ADC_CONFIG register address D0h;
            send two bytes of data, identical to that in Initialization except to set bit2=0 (triggered);
            if (i=NumberOfINA233-1) send STOP Condition;
            i++;
        }
    }
    INA233 Read
    {
        Read each individual device; data processing
    }
}
```

7 References

- Texas Instruments, *INA233 High-Side or Low-Side Measurement, Bidirectional Current and Power Monitor With I2C-, SMBus-, and PMBus-Compatible Interface* data sheet.
- Texas Instruments, *INA233EVM Evaluation Board and Software Tutorial* user guide.
- PMBus.org, *Power System Management Protocol Specification Part I – General Requirements, Transport And Electrical Interface*

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