

Expanding Analog Input Channels in Grid Applications (Using 16-Channel, 16-Bit, 1-MSPS Dual Simultaneous-Sampling ADC)



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ABSTRACT

This application report describes the ADS8686S 16-bit, 16-channel 1-MSPS simultaneously sampling ADC device features and performance in the following applications:

- Requiring an increased number of analog input channels with integrated analog front end and low temperature drift reference
- Scalable sampling rate covering protection and measurement requirements (including sampling requirements as per IEC61850-9-2)
- Measurement of analog inputs over wide input range with low measurement accuracy drift over wide temperature
- A simple interface to the host processor with the option to isolate the interface using digital isolators leveraging some of the unique features like the programmable filters, programmable oversampling rate and 20% overrange to improve the end equipment performance

This document provides an overview of the TIDA-01576 TI reference design which showcases the ADS8686S device. Its features include:

- Scaling the analog inputs to ADC input range using precision gain amplifiers or instrumentation amplifiers
- Accurate measurement of AC voltage and current over wide input
- Measurement accuracy drift over -15 to $+80^{\circ}\text{C}$ temperature
- Increased measurement range without affecting the performance using 20% overrange capability

This application note also provides an overview on using flexible sequencer modes to achieve pseudo-simultaneous sampling.

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1 Grid Infrastructure Overview

Grid infrastructure includes power generation using conventional (nuclear, thermal) and renewable (solar, wind, hydroelectric) resources, transmission of generated power over long distance at high voltages to reduce losses and distribution of power by stepping down the high voltage to levels usable by different industrial and residential consumers.

1.1 Power - Transmission and Distribution

Power generated at remote generating stations has to be transmitted over long distances to industrial , commercial and residential consumers. Transmission of power at higher voltage levels is the most economical approach. Transformers are used to step-up the generated voltage to the transmission levels. High-Voltage AC (HVAC) was used for power transmission conventionally and many of the utilities are migrating to High-Voltage DC (HVDC) transmission due to the advantages and flexibility offered. Substations are located along the path of the transmission lines to step down the high voltage based on the consumers being serviced (industrial, commercial) and power requirement for further distribution. At the distribution level, the power is further stepped down to the levels that can be directly used by consumers. Generated power goes through multiple transformations before it reaches the consumers safely.

1.1.1 Power - Transmission and Distribution Network Requirements

Some of the critical requirements for power transmission and distribution network performance include:

- Providing reliable and uninterrupted power to customers located over a wide range
- Efficient, reliable and safe transmission
- Management of load based on generation and demand
- Ensuring there is minimal or no unwanted trips or power interruptions
- Providing fast protection during faults (temporary or permanent) saving assets, humans, and environment
- Fast identification of faults and restoration
- Minimizing transmission and distribution losses
- Accurate billing of consumers maximizing revenue and detection of power tampering
- Asset monitoring by automation, increasing the equipment life by preventive or predictive maintenance

2 End Equipment

An end equipment performs a designated function (single or multiple) based on the configuration and the installed location. Primary equipment is mostly electro-mechanical or mechanical equipment that are used to generate, distribute, switch and manage the electrical network and include power transformers, HV (high voltage) or MV (medium voltage) transmission lines, load break switches, disconnect switches, and circuit breakers.

Secondary equipment is installed along with the primary equipment and are used to protect, control, monitor, and manage the primary equipment.

2.1 Secondary Equipment

Commonly used secondary equipment in grid for protection, control, and monitoring includes protection relays, terminal units (RTU, DTU, FTU), circuit breakers, contactor, power quality analyzers, merging units, bay controllers, recloser and fault indicators. The secondary equipment used along with the primary equipment in transmission and distribution networks vary in complexity and perform varied functions. Some of the functions performed include:

1. Protection of transmission lines, power transformers, feeders, disconnect switches, circuit breakers, and large customer loads
2. Control, monitoring and interlocking of feeders, load switches, and circuit breakers
3. Measurement of generated, transmitted and consumed power for revenue metering and loss estimation.
4. Power quality monitoring and analysis for maintaining the required network power quality, optimizing compensation, reducing losses, and extending equipment life
5. Substation automation including merging unit, bay controller, gateways implementing real time protocols for automation with redundancy
6. Distribution automation including automatic recloser and fault indicators for protection of MV transmission lines and faster fault location, identification, and restoration

2.1.1 Secondary Equipment Performance Requirements

Some of the critical performance requirements for the secondary equipment includes:

Measurement (AC analog input module): Accurate measurement of wide AC voltage and current inputs is the key for reliable system performance. The analog inputs are used for protection, control, measurement, monitoring, and diagnostics.

Signal processing (Processor module): Real time processing of the measured analog values and execution of algorithms provides accurate measurement and trip time performance.

Communication (Communication module): High-speed Ethernet and legacy serial interface for networking of multiple end equipment for data exchange and configuration. Redundancy and reduced latency is critical for automation, improving the overall system performance and availability.

Digital and Analog IOs (Digital or Binary input module, Contact or digital output module, DC analog input module and DC analog output module): used for interlocking and status indication within the electrical network. These are also used for remote commanding and control.

3 AC Analog Input Module

AC analog modules with onboard precision, multichannel ADC are used for measurement of analog inputs (voltage or current).

3.1 Functional Blocks of Wide Input AC Analog Input Module

Figure 3-1 illustrates the main functional blocks on an AIM.

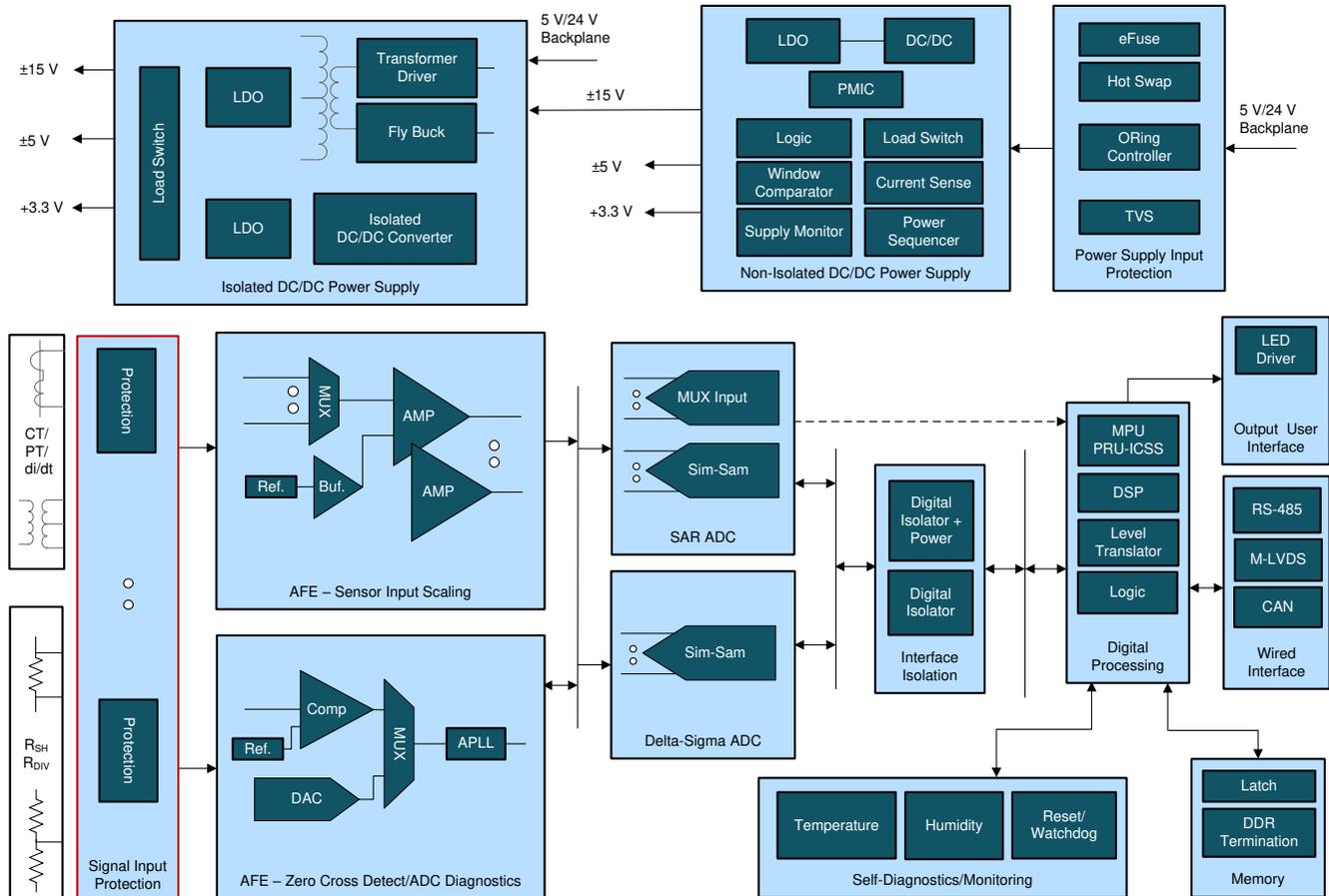


Figure 3-1. Wide Input Range AC Analog Input Module End Equipment Reference Diagram

- *Voltage* sensor for transforming the 110 V or 230 V secondary voltages and *Current* sensor for transforming the 1-100 A secondary currents to a measurable level
- Gain scaling amplifier based on precision op amp or instrumentation amplifiers can be used to scale the sensor output to the ADC input range of ± 10 V with minimum drift over temperature
- The input to the ADC is subjected to transients generated during normal operation of the equipment and needs to be protected for reliable operation
- Precision ADC with resolution of 16-bit or more, with input ranges up to ± 10 V or ± 5 V can be chosen
- ADC with higher sampling rate and integrated features simplifies system design
- A DC/DC converter with input overload protection is used to generate split-rail power supply
- The ADC interfaces to the host using a serial- or parallel-interface for processing the sample values and configurations
- A comparator configured for zero cross detection to implement coherent sampling
- Optionally, the ADC serial interface can be isolated from the host using digital isolators with integrated or external DC/DC power

Figure 3-2 shows AFE for performance testing of ADS8686S using ADS8686SEVM-PDK interfaced to PHI host controller.

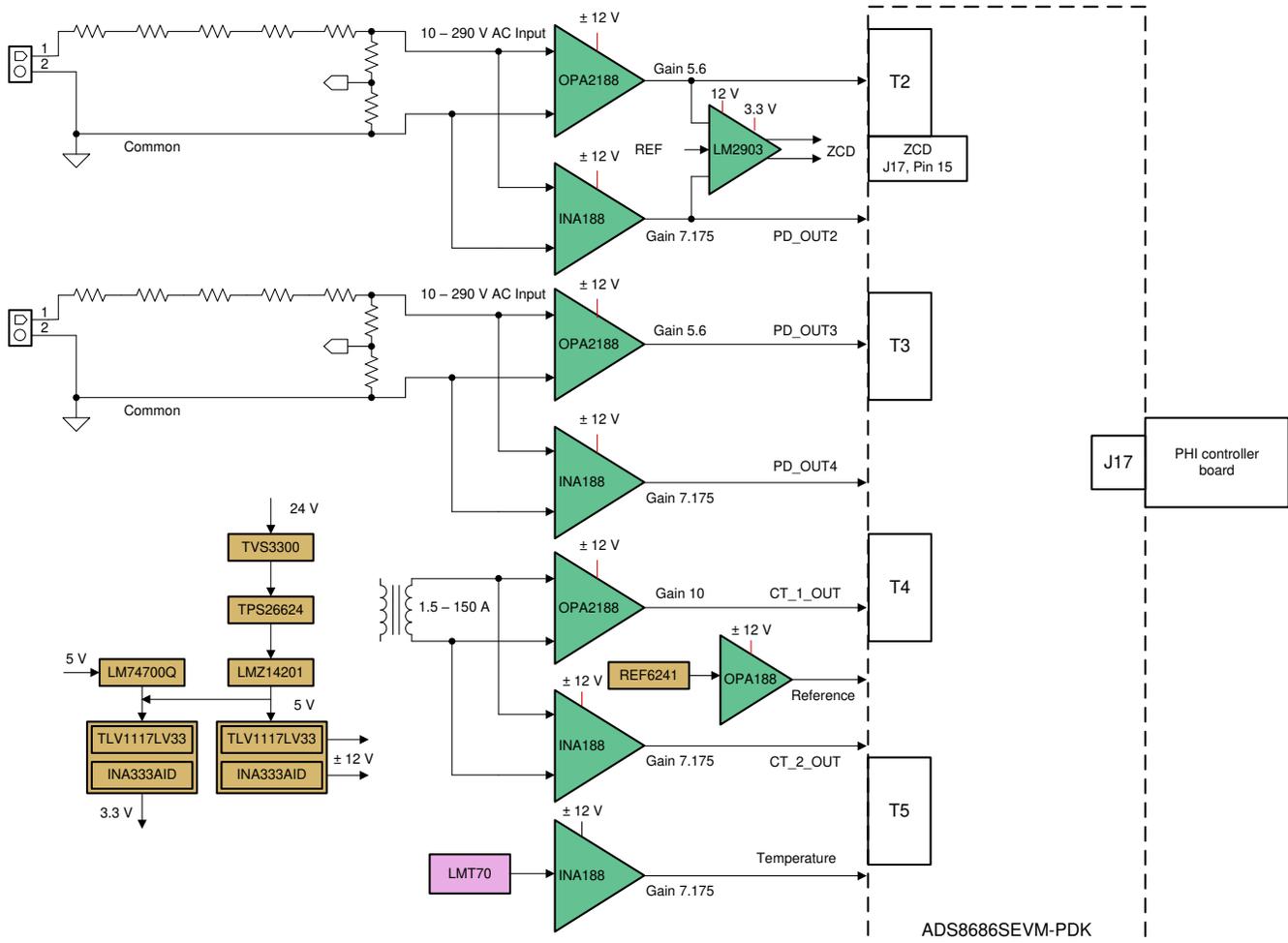


Figure 3-2. ADS8686SEVM-PDK Based AC Analog Input Module

3.2 Need for Expanding (Increasing) Analog Input Channels

With increased requirements for improving operational efficiency and system performance, utilities are looking at secondary equipment with an increased number of analog and digital channels. The following lists a few applications:

Power transmission and distribution: With increasing focus on improving power transmission and distribution efficiency, extending the primary equipment life, reducing power interruptions and improving power quality, more functions are being added to the convention grid secondary equipment. Along with protection, control, monitoring and diagnostics functions are being added. Addition of additional functions requires measurement of additional analog input channels for monitoring the equipment at multiple locations, increasing dynamic range by sampling the same analog inputs using multiple ADC channels with different input ranges and redundant sampling of inputs using multiple ADC channels for continuous diagnostics.

Substations: Traditional centralized control rooms in substation stations are being upgraded to smaller kiosks and hence secondary equipment form factor is reducing. One way to reduce size is to integrate multiple functions into the next-generation secondary equipment with the capability to capture and process more analog inputs. Conventionally, each of the feeders has dedicated equipment for performing the required protection and monitoring function and are being replaced by a single equipment capable of monitoring multiple feeders and performing multiple functions on each feeder.

3.3 Solutions for Expanding Analog Input Channels

There are multiple approaches to integrating multiple functions and the key is the capability to extend analog input channels. There are multiple approaches to expand the number of analog channels:

- Modular design analog input modules are based on the requirement that the system is configured with the required number of modules. The scalability is limited due to the fixed number of available slots and also increases cost.
- An alternative approach is to have multiple devices on one board, daisy chain or interface to the devices using external logic. The design gets complex when more channels are required.
- An optimized approach is to use an ADC with higher channel count and a multiplexer. Multiplexing limits the data output rate and introduces sampling delay between channels.

The solution to overcome these limitations is to use an integrated solution: the ADS8686S, 16-channel, 16-bit dual simultaneous-sampling SAR ADC with 1-MHz data output rate.

4 ADS8686S 16-Bit, 16-Channel 1-MSPS Dual Simultaneous-Sampling ADC

The ADS8686S is a 16-bit digital acquisition system (DAS) designed for a variety of generation, transmission and distribution applications, including protection relays, terminal units (remote terminal units (RTU), distribution terminal units (DTU), and feeder terminal units (FTU), bay controller, merging unit and other grid applications. The ADS8688S device supports dual simultaneous sampling of input channels. The device can be configured to accept $\pm 10\text{-V}$, $\pm 5\text{-V}$, or $\pm 2.5\text{-V}$ bipolar inputs with a 20% overrange option using a single 5-V supply, while sampling at throughput rates up to 1 MSPS with ≥ 90 dB SNR.

4.1 16 Channel Data Acquisition System (DAQ) for Grid Infrastructure Protection and Power Automation (8 × 2)

Figure 4-1 shows the ADS8686S block diagram.

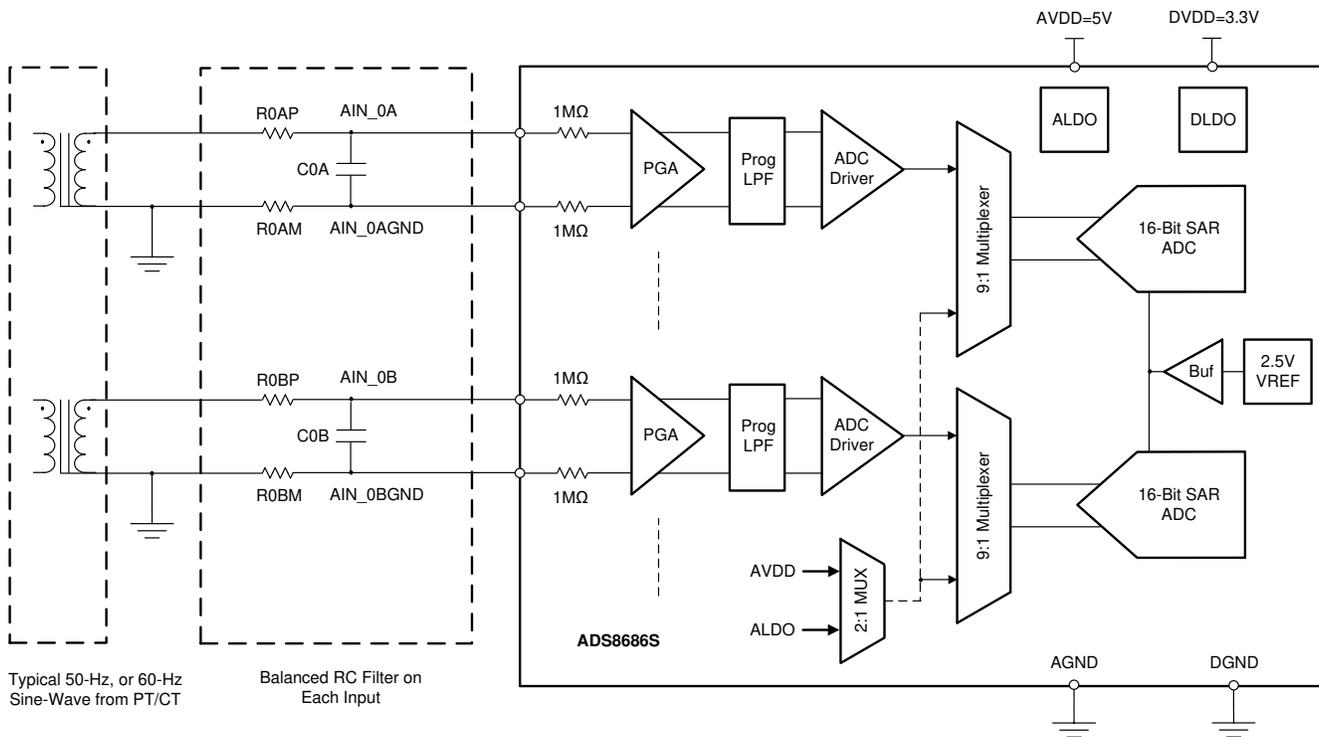


Figure 4-1. ADS8686S Based DAQ for Grid Applications

Some of the key features of the ADS8686S device follow:

- 16-channel, 16-bit ADC with integrated analog front-end
- Dual simultaneous sampling: 8 × 2 channels
- Supply:
 - Analog: 5 V
 - Digital: 1.8 V to 5 V
- Constant 1-MΩ input impedance front-end
- Independently programmable input ranges with 20% overrange
- Programmable low-pass filter – 15 kHz, 39 kHz, 376 kHz
- Excellent DC and AC performance
- On-chip reference and reference buffer
- Excellent temperature performance
- Optional cyclic redundancy check (CRC) error checking
- High-speed serial and parallel interfaces
- Highly-configurable channel sequencer to reduce the sequencing overhead on the backend controller or processor

ADC features users can use for performance improvements are discussed in the following sections:

4.1.1 Coherent and Simultaneous Sampling

CONVST (conversion start) is a logic input to control the conversion start for channel group A and channel group B of the ADC. The rising edge of the CONVST pin, when BUSY is low, initiates a new conversion on the selected input channel pair from channel group A and channel group B. By controlling the CONVST timing based on the input frequency and the number of required samples per cycle, coherent sampling can be achieved. Coherent sampling improves measurement accuracy by reducing the spectral leakage.

For normal mode and sequencer mode of operation, every CONVST signal performs one conversion of the selected channel pair based on the oversampling setting. For burst mode of operation only one CONVST signal is needed for the sequencer to cycle through the channel sequence. The BUSY signal is held high during this duration.

In hardware mode, simultaneous sampling is restricted to the corresponding A and B channel (that is, channel AIN_0A is always sampled with channel AIN_0B). In software mode, any AIN_nA channel can be selected with any AIN_nB channel for simultaneous sampling.

4.1.2 Interface

A flexible digital interface supporting serial, parallel, and byte communication enables the device to be used with a variety of host controllers.

4.1.3 Diagnostics

The ADS8686S supports a CRC checksum mode to improve interface robustness by detecting errors in data. The CRC feature is available in both software (serial, byte, and parallel) mode and hardware (serial only) mode.

4.1.4 Accuracy

The ADS8686S can achieve Class 0.2 measurement accuracy because its on-chip ADCs have ≥ 90 dB of SNR. Higher SNR performance of ≥ 92 dB can be achieved by using the on-chip oversampling mode.

4.1.5 Simplicity

The ADS8686S is a 16-bit, DAS that supports dual simultaneous sampling of 16 channels. This input scheme simplifies system design by removing phase shift associated with voltage and current channels. In addition, it operates from a single 5-V supply, which simplifies the power supply design.

4.1.6 Reduced System Cost

The ADS8686S is a 16-channel DAS that is highly integrated and can accept a variety of input signal ranges (± 10 V, ± 5 V, ± 2.5 V) with 20% overrange. The analog front end features a 1-M Ω , high impedance, very low drift, input buffer. This eliminates the need for external protection circuits or external signal conditioning ICs, greatly minimizing the system cost.

4.2 Enhancements

Some of the ADC features along with external buffers or TVS protection can be used for improving the system performance. Some of the enhancements are listed below:

4.2.1 Improving ADC Performance Using an Input Buffer

When the ADC input channels are left open or the sensor connected to the ADC input fails open, due to the internal AFE structure a constant 2-V output is measured by the ADC. In grid applications where an output zero during sensor open conditioned is required, it is recommended to buffer the analog inputs using op amps. The implementation is discussed in the TI reference design: [TIDA-010008 – Flat-Clamp TVS based Reference Design for Protection Against Transient for Grid Applications](#) .

4.2.2 Input Protection Using Flat-Clamp TVS

The ADC inputs are exposed to transients during normal operation and have to be protected. A TVS can be recommended to protect the ADC inputs against transients. Use of flat-clamp TVS protects the analog inputs against overvoltage and transients. Refer [TIDA-010008 – Flat-Clamp TVS based Reference Design for Protection Against Transient for Grid Applications](#) for more details on using flat-clamp TVS for protection of analog inputs.

4.2.3 Achieving Pseudo-simultaneous Sampling by Using the ADS8686S Flexible Sequencer and Burst Mode

In grid power systems protection and measurement applications, voltage and currents are sampled simultaneously to minimize phase errors reducing the measurement error and compensation overheads ensuring faster and repeatable trip time characteristics.

Some applications implement instantaneous protections that require the phase voltages and currents to be sampled simultaneously. Flexible sequencer and the burst mode options provided by the ADC can be used to achieve pseudo-simultaneous sampling.

4.2.3.1 Sequencer

The on-chip sequencer can be enabled to scan the channels in a preprogrammed manner. The SEQEN pin is a digital input pin that enables the internal channel sequencer mode for data capture in the hardware mode of operation. In the sequencer mode of operation, the CHSELx pins configure the settings for the sequencer. The sequencer enables selection of the internal MUX connection in a predetermined order. This architecture helps reduce the software overhead on the host controller to configure the next channel for conversion. A complete set of sequencer functionality and configurability is available in software mode. The sequencer stack has 32 unique configurable sequence steps. All channels, including the diagnostic channel, can be randomly programmed in any order. Additionally, any channel AIN_nA input can be paired with any channel AIN_nB input or diagnostic channel. The sequencer can be operated with or without the burst function enabled. With the burst function enabled, only one CONVST pulse is required to convert every channel in a sequence. With burst mode disabled, one CONVST pulse is required for every conversion step in the sequence.

In hardware mode, the sequencer has limited functionality. The sequencer always selects a particular channel pair (for example, AIN_nA and AIN_nB).

4.2.3.2 Burst Sequencer

The ADS8686S offers an additional feature for burst mode capture. This feature is applicable only if the sequencer feature is enabled. With the burst feature enabled, one CONVST pulse initiates conversion of all channels configured in the sequencer. Thus, for a sequencer configured for four channel pairs, only one CONVST pulse must be provided in BURST with the sequencer configuration instead of four CONVST pulses in the sequencer-only configuration. The conversion results are presented on the data bus (parallel, byte, or serial) in the same order as the programmed sequence.

4.2.4 Isolated Interface

In HV transmission and MV distribution applications where the reliability of the secondary equipment is a critical factor for the overall system performance, the analog input module is isolated from the host. Use of digital isolator simplifies the design and improved the reliability. The ADC is configured to interface with the host in serial mode and all the interface signals are isolated. Digital isolators with integrated power or digital isolators with external isolated DC/DC converters are used. Use of reinforced isolation increases system reliability.

[Figure 4-2](#) shows the isolated interface module test setup showcased in TIDA-01576.

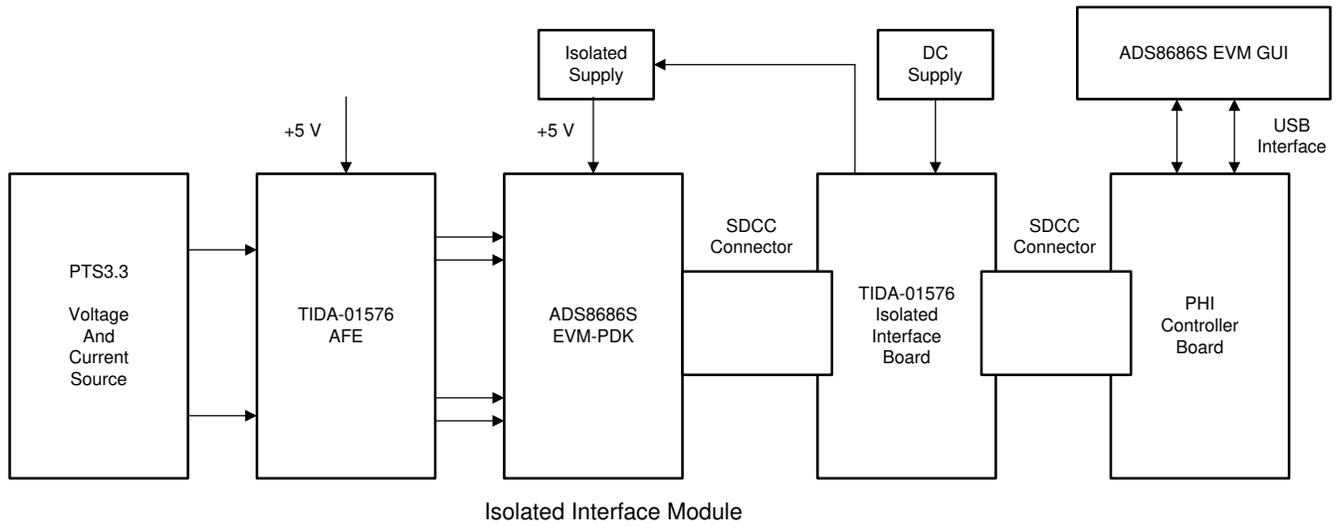


Figure 4-2. Isolated Interface Module Test Setup

5 TIDA-01576 TI Reference Design

The [High accuracy analog input module reference design with 16-bit 1-MSPS dual simultaneous-sampling ADC](#) from TI provides a solution for accurate measurement of 16-channel wide AC analog inputs (voltage and current) using precision 16-channel 16-bit 1-MSPS dual simultaneous-sampling ADC covering protection and measurement requirements (including sampling requirements as per IEC61850-9-2) simplifying system design, improving trip time performance and reliability. Coherent sampling of the analog inputs with configurable samples per cycle and programmable oversampling rate improves measurement performance. The reference design performance has been tested over a wide temperature range with internal or external reference configured and no appreciable variation in error was observed.

The design showcases the design of an AC analog input module using the ADS8688S, 16-channel 16-bit 1-MSPS dual simultaneous-sampling ADC with integrated analog front-end.

Optionally, an isolated interface between ADS8686SEVM-PDK and the host PHI controller is showcased for improved performance and safety in harsh operating conditions using a digital isolator with external isolated DC/DC based power supply. No change in the ADC performance was observed.

For more information, see the [TIDA-01576 High accuracy analog input module reference design with 16-bit 1-MSPS dual simultaneous-sampling ADC](#) tool folder.

5.1 Test Results

The section provides details on the test setup and results for the ADS8686SEVM-PDK based analog input module.

5.1.1 Test Setup

Figure 5-1 shows the test setup for testing the performance of the TIDA-01576 AFE interfaced to the ADS8686SEVM-PDK.

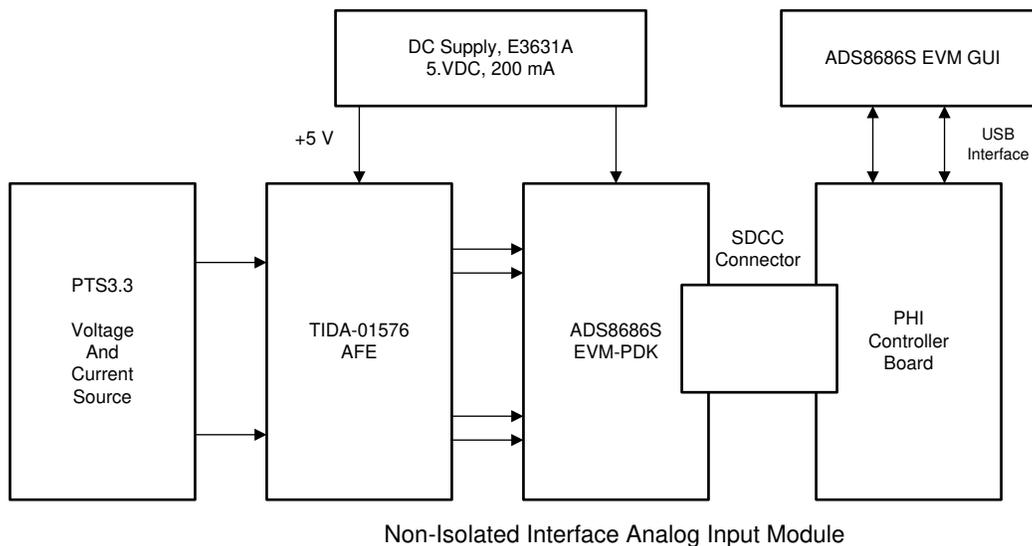


Figure 5-1. ADS8688SEVM-PDK Based Analog Input Module

A customized GUI was used for evaluating the TIDA-01576 TI reference design performance.

5.1.2 Voltage and Current Measurement Accuracy

Table 5-1 provides accuracy performance results for linear temperature variation. Measurements were performed by varying the input voltage and the minimum value, maximum value, and difference over a wide input are summarized.

Table 5-1. Voltage and Current Measurement Accuracy

Test Type	Description	ADC Channel	% Error Measured		
			Minimum	Maximum	Difference
Accuracy testing with external reference configured, 39-kHz filter	±10-V input range with 10 V to 290 V input	5A	-0.112	-0.032	0.080
		5B	-0.088	-0.011	0.077
		6A	-0.091	-0.007	0.084
		6B	-0.110	-0.032	0.078
	±10-V input range with 10 V to 360 V input	4A	-0.144	-0.077	0.067
		4B	-0.191	-0.094	0.097
		7A	-0.188	-0.121	0.067
		7B	-0.138	-0.042	0.096
	±10-V input range with 1 A to 100 A input	4A	-0.208	0.188	0.396
		7B	-0.206	0.188	0.394
	±10-V input range with 1.95 A to 165 A input	5A	-0.217	0.209	0.427
		6B	0.057	0.288	0.231
Accuracy testing with internal reference configured, 39-kHz filter	±10-V input range with 10 V to 290 V input	1A	-0.077	0.023	0.100
		1B	-0.056	0.039	0.095
		2A	-0.056	0.042	0.097
		2B	-0.073	0.016	0.088
	±10-V input range with 10 V to 360 V input	0A	-0.094	-0.005	0.090
		0B	-0.150	-0.053	0.096
		3A	-0.146	-0.051	0.095
		3B	-0.102	-0.005	0.097
		5A	-0.104	-0.033	0.071
		5B	-0.080	-0.016	0.064
Accuracy testing with external reference configured, 15-kHz filter	±10-V input range with 10 V to 290 V input	6A	-0.084	-0.011	0.072
		6B	-0.102	-0.016	0.087
		4A	-0.138	-0.046	0.092
		4B	-0.185	-0.094	0.091
	±10-V input range with 10 V to 360 V input	7A	-0.183	-0.091	0.091
		7B	-0.133	-0.041	0.092

5.1.3 Measurement Accuracy Drift Over Temperature

Table 5-2 provides accuracy results for linear temperature variation. Measurements were performed by varying the input voltage. The minimum value, maximum value, and difference over a wide input are summarized in Table 5-2.

Table 5-2. Variation in Measurement Accuracy Over Temperature

Test Type	Input Voltage	ADC Channel	% Error Measured		
			Minimum	Maximum	Difference
Accuracy testing with external reference configured and linear temperature variation in °C with ±10-V input range, 39 kHz filter 25, 55, 80, 25, -15, 25	280 V	5A	-0.121	-0.063	0.058
		5B	-0.096	-0.039	0.057
		6A	-0.093	-0.042	0.050
		6B	-0.119	-0.061	0.058
		4A	-0.147	-0.119	0.028
		4B	-0.194	-0.164	0.030
		7A	-0.191	-0.162	0.029
		7B	-0.142	-0.112	0.030
	200 V	5A	-0.112	-0.085	0.027
		5B	-0.086	-0.062	0.024
		6A	-0.089	-0.065	0.024
		6B	-0.108	-0.083	0.025
		4A	-0.133	-0.096	0.037
		4B	-0.180	-0.144	0.036
		7A	-0.179	-0.141	0.037
		7B	-0.129	-0.092	0.037
	50 V	5A	-0.070	-0.029	0.041
		5B	-0.047	-0.009	0.038
		6A	-0.047	-0.011	0.036
		6B	-0.069	-0.029	0.040
		4A	-0.102	-0.054	0.048
		4B	-0.150	-0.102	0.048
		7A	-0.143	-0.099	0.044
		7B	-0.097	-0.051	0.046
	10 V	5A	-0.043	-0.014	0.030
		5B	-0.026	-0.001	0.025
		6A	-0.026	0.009	0.035
		6B	-0.048	-0.023	0.025
		4A	-0.100	-0.062	0.038
		4B	-0.137	-0.116	0.020
		7A	-0.135	-0.098	0.037
		7B	-0.076	-0.041	0.035

6 Summary

Using a 16-channel ADC simplifies AC analog input module design in applications requiring higher number of analog input channels or for increasing the dynamic range. The ADS8686S device is a dual simultaneous-sampling 16-channel, 16-bit ADC with configurable input ranges with 20% overrange. A flexible channel sequencer for sampling reduces software overhead. The ADS8686S has excellent accuracy performance over wide voltage inputs, current inputs and temperature range.

7 References

References used in this application note is listed below:

- Texas Instruments, [ADS8686S, 16-channel 16-bit 1-MSPS dual simultaneous-sampling ADC with integrated analog front end \(AFE\) product folder](#)
- Texas Instruments, [ADS8686S 16-channel 16-bit 1-MSPS dual simultaneous-sampling ADC performance demonstration kit \(PDK\) ADS8686SEVM-PDK](#)
- Texas Instruments, [Isolated power architecture reference design for communication and analog input/output modules](#)
- Texas Instruments, [Non-isolated power architecture with diagnostics reference design for protection relay modules](#)
- Texas Instruments, [Flat-Clamp TVS based Reference Design for Protection Against Transient for Grid Applications](#)
- Texas Instruments, [High-efficiency, low-emission, isolated DC/DC converter-based analog input module reference design](#)
- Texas Instruments, [Introduction to HVDC Architecture and Solutions for Control and Protection Application Report](#)

8 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (June 2020) to Revision A (February 2021)	Page
• Updated the numbering format for tables, figures and cross-references throughout the document.....	2

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