Introduction to Stand-Alone Data Converters - Review, Analysis and Design Orientation

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Abstract: This paper includes a basic review, analysis, and interesting insights, oriented to designers when power consumption is a critical constraint, of Stand-Alone Data Converters. These data converters are an indispensable part of the analog design technique and the only bridge to establish an adequate communication link between analog and digital devices. In fact, this article is dedicated to showing the principal types of the analog-to-digital converters (ADC) and digital-to-analog converters (DAC) families of data converters popular in modern analog design techniques. In fact, these data converters are also cost-effective devices because of the huge number of existing and newly developed solutions with their significant practical features providing more relevant applications in specific type of ADC or DAC process. The overview of data conversion, ADC and DAC data converters, communication bus to Micro Controller Units (MCU), and benefits of data conversion are described.

Keywords: ADC/DAC, MCU, LED, VCC, LSB, ENOB, THD, IC, SPI, CAN

1. Introduction

Today, many electronic applications or embedded systems include a combination of digital and analog circuits in which the digital part is used to receive information (signal) from an analog circuit and vice versa to form an analog signal out of digital information. Typically, an embedded electronic system is a microcontroller-based digital circuit, which is not able to process or to receive an analog signal directly without preliminary conversion of the analog signal into digital information as well as is not able to form the analog signal without conversion of digital information into an analog signal. Commonly, an analog circuit may include analog sensors of temperature, pressure, light intensity, current, voltage, acoustic (microphone) and etc. Besides, analog circuits take place in such applications as: music reproduction technologies; digital communication services or data voice service; signal data processing in digital storage oscilloscopes, TV tuner cards, digital imaging and video systems, medical equipment and other scientific instruments.

The ADC solutions are widely used in modern electronics to represent values of analog signals in digital form for subsequent storage or logic processing by traditional micro-controllers. In another way, the DAC solutions perform the inverse operation, by transforming the digital information into the analog form. Recently, a different memorable logic architecture has been demonstrated in which the same storage devices play the role of gate and latch. Here is proposed an approach to ADC and DAC conversion with memorable devices in which the digital value of the signal is written into the states of storage systems. This approach is thus directly compatible with the memorable logic architectures recently proposed, and can also be used in chips interfacing the usual electronic components. Thus, the proposed methodology could be also implemented with capacitors and inductors with memory, which in principle can be made almost dissipationless [1, 2].

The common electric voltage and current signals are often referred to as analog signals, which must be converted to digital signals prior to input into computers. As stated, the ADC units are used to convert analog signals to digital signals. Inversely, the computer output that is in digital form must sometimes be converted to an analog signal prior to input to an electronic or electrical device. Thus, the DAC units are used to perform this operation. In any system, two kinds of signals can be measured or generated, known as analog and digital signals. Thus, analog signals assume a continuous range of values, whereas digital signals assume a finite number of values. As an example, a binary signal is a digital signal, which assumes one of two values, either on or off (1 or 0). A typical example of an analog signal is the value of the temperature in an oven. The temperature, being an analog variable, can assume an infinite number of intermediate values. In fact, because of the finite precision and limited storage of a computer, the digital representation is used. The precision of the measurement is said to be limited to (n) significant digits. The DA converter functions by using different gains for each input of the summer. If the same voltage is applied to each of the summer inputs, then each input will add a different component to the total output voltage. By selecting appropriate values for each of the summer input resistors, the gains or weights of each input can be set.

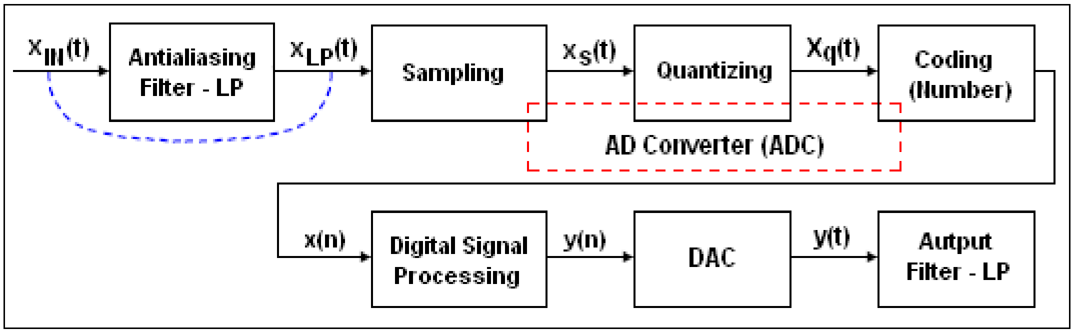

Figure 1. Block Diagram of Digital Signal Processing

Power quality components can easily be found for a sinusoidal voltage and current of same frequency. In power electronics, switching devices like diodes are not on for entire the cycle. The switches are on for some portion of the cycle and off for other portions. Therefore, the output waveforms from power electronic devices like rectifiers are periodic but not sinusoidal, so the equations available for pure sinusoidal waveforms cannot be applied in power electronics [1, 3 - 5].

2. Overview of Data Conversion

The devices that perform the interfacing function between analog and digital worlds are ADC and DAC converters, which together are known as data converters. The input to the system is a physical parameter such as temperature, pressure, flow, acceleration, position, etc., which are analog quantities. The parameter is first converted into an electrical signal by means of a transducer, once in electrical form all further processing is done by electronic circuits, which are illustrated in **Figure 1.**

Thus, an analog to digital converters are an electronic circuit which accepts an analog input signal, usually a voltage V(t) and produces a corresponding digital number at the output when the resultant digital word goes to a computer data bus or to the input of a digital circuit.The electronic analog-to-digital data converter requires a small amount of time to perform the quantizing and coding operations.

The time required to make the conversion depends on: the converter resolution, the conversion technique, and the speed of the components employed in the converter. The conversion speed required for a particular application depends on the time variation of the signal to be converted and on the accuracy desired. For the specific case of a sinusoidal input signal, the maximum rate of change occurs at the zero crossings of the waveform, which equation is:

$$\Delta V = T_A \cdot d/dt\,(V_M \sin\omega t) = T_A \cdot (V_M \cos\omega t) = |\omega{=}0| = T_A\, V_M\, \omega \qquad (1)$$

Where ΔV = amplitude uncertainty, T_A = aperture time, d/dt = differential operator, V_M = amplitude of the input signal, and ωt = angular frequency ($\omega t=3\pi/2$).

In such a way, the resultant error as a fraction of the peak-to-peak full-scale value can be presented by following equation:

$$\varepsilon = \Delta V/2V_M = T_A V_M\, \omega/2V_M = T_A V_M\, 2\pi\, f/2V_M = \pi \cdot f \cdot T_A \qquad (2)$$

Where the value of ω = angular frequency, f = frequency, and π = mathematical constant of 3.14 denotation. From this result, the aperture time required to digitize a 1 kHz signal to 10 bits resolution can be found. The resolution required is one part in 210 or approximately 0.001, which value can be provided by the following relation:

$$T_A = \varepsilon/\pi\, f = 0.001/3.14 \cdot 10^3 \approx 302 \cdot 10^{-9} \qquad (3)$$

The result is a required aperture time of just 320ns. In fact, it is evident that it is hard to find a 10-bit AD converter to perform this conversion at any price. However, the world and humans encounter as an analog playground, but nowadays, nearly all signal processing related to that world is performed digitally. Prior to the digital age, physical variables were measured in analog and were subsequently processed in analog too. Today, physical variables are still measured in analog form, and the resulting signals are immediately converted to digital form for processing, transmission, or storage on computers and digital devices [2, 6 - 8].

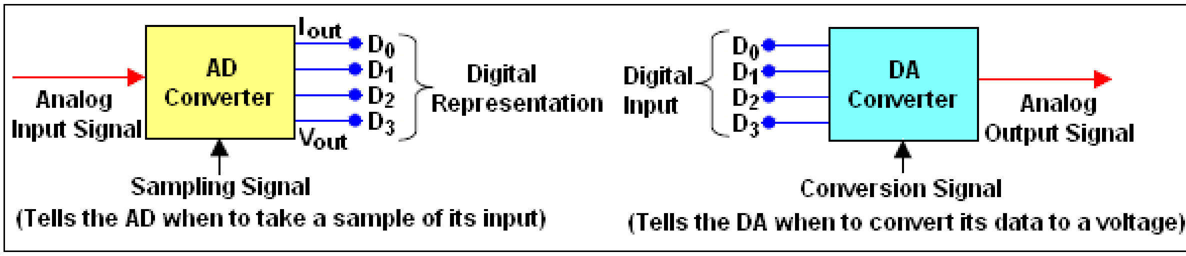

Figure 2. Block Diagram of Digital Signal Processing

In reality, practitioners can use a microcontroller as a counter to count up the DA converter, while at the same time they will feed the comparator devices output into the microcontroller. The microcontroller program checks the comparator state each increment of the counter. Once the comparator goes low then the count stops, and Light Emitting Diode (LED) units can be connected to the outputs of the binary counter to indicate the final value read in binary. At this point, it will be important to limit the LED current to less than 3mA to prevent the loading of the microcontroller counter pins.

This is important because if the LED units load the pins then the output of the microcontroller will not reach Voltage at the Common Collector (VCC) and it will produce a large error in the DA converter output voltage. Interfacing between nature's analog world and human-made digital systems requires a special class of circuits. Two important members of the interface family are the AD converter, and the DA converter, which is illustrated in **Figure 2.** These diagrams illustrate these conversion concepts in block form. In this laboratory assignment, the practitioner will build and otherwise become acquainted with each type of circuit. The calculation of the outcome current (Volt) can be provided by the following quotation:

$$Vout = Vref/2^N \cdot B = Vlsb \cdot B \quad (4)$$

Where Vref = reference voltage, N = resolution of the conversion, B = binary value, Vlsb = voltage that corresponds to the Last Significant Bit (LSB) value. However, the calculation of the maximal outcome current (Vout-max) and LSB voltage can be provided by the following quotation:

$$Vout\text{-}max = Vref/2^N \cdot (2^N - 1 = FS \quad \text{where FS = full scale and when Vout-min = 0} \quad (5)$$

$$Vlsb = Vref/2^N \quad (6)$$

The data conversion of an analog signal into digital information and vice versa can be realized only with the help of the ADC and the DAC data converters. Namely, the ADC and DAC can be used as an integrated entire unit with an MCU or as a standalone unit, which is predominantly considered in the article. The illustration of the sequential process of AD and DA conversion is shown in **Figure 3.**

Theoretically, the digital circuits used in programmable devices have only two states and by convention, these two states are denoted using the symbols 0 and 1. With only two states/symbols available numbers have to be represented as powers of 2 rather than powers of 10. As in the decimal system, counting in binary starts with 0 and this is followed by 1. In the decimal system the next number is representing by symbol 2. However in binary, there are only two symbols and so the next number has to be represented by increasing the power of 2 and so when counting in binary 1 is followed by 10.

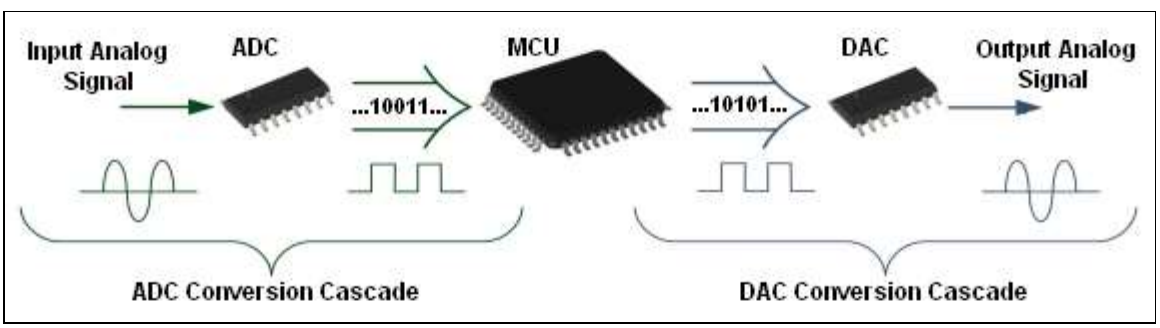

Figure 3. Solutions of AD and DA Processing Sequence

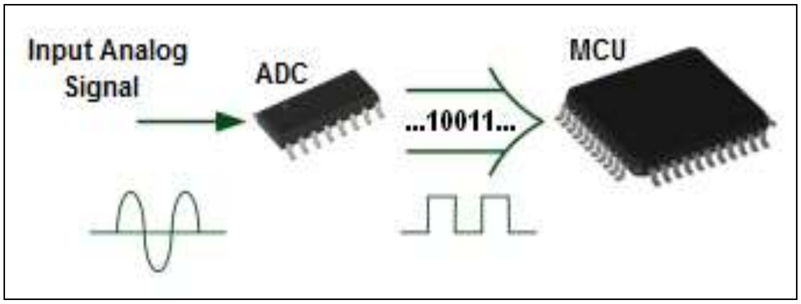

Figure 4. Cascade of the Circuit for AD Conversion

In such a way, following the example of decimal, this is equivalent to the decimal number 1x21+0x20. More generally as in decimal numbers, any binary number can be understood using the associated powers of 2, so for example:

$$1010 = 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = 1 \times 8 + 0 \times 4 + 1 \times 2 + 0 \times 1 = 10 \quad (7)$$

Each the symbol in a binary number is known as a bit and a binary number is a list or string of bits. The first bit in a string is known as the most significant bit and the last one is known as the least significant bit. One convention is to label each bit with a subscript corresponding to the equivalent power of 2, thus that for example the least significant bit (which represents the multiple of 2^0 within a binary number) is b^0. In this convention a four-bit the number is therefore b^3 b^2 b^1 b^0 and the equivalent number is [5, 9 - 14]:

$$\text{Decimal} = b_3 \times 2^3 + b_2 \times 2^2 + b_1 \times 2^1 + b_0 \times 2^0 \quad (8)$$

3. Analog-to-Digital Data Conversion

As stated above, AD data conversion is an indispensable key element of any electronic digital circuit that needs to be conjugated or exploited in combination with analog electronic circuits. Therefore an application, in which a certain AD data converter should be used, gives certain requirements to parameters and type for selecting an AD conversion. The given requirements and type should be assured by the selected ADC for a particular application. The Analog-to-Digital conversion cascade is illustrated in **Figure 4.**

In fact, the ADC is a linkage between the analog (linear) world of transducers and the discreet world of processing the signal and handling the data, while DAC carries out the inverse function. The whole ADC conversion process is shown in **Figure 5.** There are mainly two steps involves in the process of digital conversion such as Sampling and Holding and Quantizing and Encoding.

1. Sampling and Holding – In the process of Sample and Hold (S/H), the continuous signal will get sampled and freeze (hold) the value at a steady level for a particular least period of time. At this point, this S/H process is done to remove variations in the input signal, which can alter the conversion process and thereby increases the accuracy. Thus, the minimum sampling rate has to be two times the maximum data frequency of the input signal.

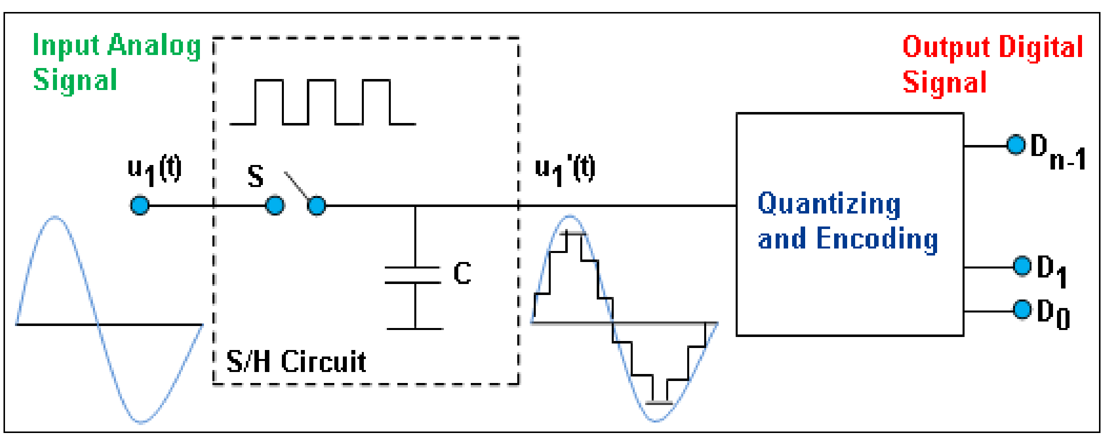

Figure 5. Complete AD Conversion Process

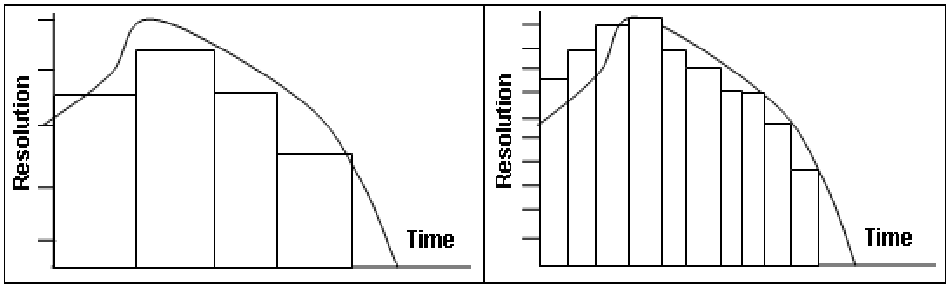

Figure 6. Low and Increased Accuracy of AD Conversion Process

2. Quantizing and Encoding – For understanding quantizing, it will be necessary at first to go through the term resolution used in ADC mode. It is the smallest variation in the analog signal that will result in a variation in the digital output. This actually represents the quantization error. The process of quantizing and encoding is demonstrated in **Table 1.**

Table 1. Quantizing and Encoding Process

Analog Signal			Digital o/p	Analog Signal			Digital o/p
7.5	7 →	7Δ=7V →	111	3.5	3 →	3Δ=3V →	011
6.5	6 →	6Δ=6V →	110	2.5	2 →	2Δ=2V →	010
5.5	5 →	5Δ=5V →	101	1.5	1 →	1Δ=1V →	001
4.5	4 →	4Δ=4V →	100	0.5	0 →	0Δ=0V →	000

In **Figure 6 (Left)** is illustrated sample of low accuracy, while two important methods are used for improving the accuracy in AD conversions. They are by increasing the resolution and by increasing the sampling rate, which solutions are shown in **Figure 6 (Right).** The main characteristics of an ADC for selection criteria are following: the bandwidth (the frequency range that an ADC can measure), the signal to noise ratio (characterizes accuracy of a signal measurement relative to its noise) and the dynamic range (characterized by the effective number of bits used for conversion that can be considered as the resolution of an ADC). The actual bandwidth of an ADC is characterized primarily by its sampling rate. The sampling rate depends on a frequency of digitizing signal, which means the higher digitizing frequency of an analog signal to be made, the higher sampling rate of an ADC should be chosen.

The dynamic range of an ADC is influenced by many factors, but mainly the dynamic range of the ADC is often determined by its Effective Number of Bits (ENOB) either can be characterized as resolution, since the ENOB of an ideal ADC is equal to its resolution. Operation of an ADC is close to ideal operation when an ADC operates at a sampling rate greater than twice the bandwidth of the signal, then perfect digitizing is possible and the ENOB can be considered as equal to the resolution. When the sampling rate is close or less than twice the bandwidth of the analog signal, then quantization errors may occur and the bigger number of quantization errors the less dynamic range of an ADC becomes. In other words, the presence of quantization error limits the dynamic range of an ADC, however, if the dynamic range of the ADC exceeds the bandwidth of the input signal, its effects maybe neglected.The type (architecture) of ADC is determined by its implemented technical conversion principal in the hardware of an ADC for digitizing analog signals. To some extent the signal to noise ratio of an ADC depends on the type of an ADC and the energy consumption of an ADC mainly depends on its type. The main type varieties of ADC units and their characteristics with relevant available device families and suggested applications are indicated in **Table 2** [4, 15 - 17].

4. Digital-to-Analog Data Conversion

The DAC element is a device that converts digital data (usually binary information) into an analog signal. Essentially, a DAC performs the reverse function of the ADC. Digital information obtained from the ADC or generated by MCU needs to be transferred to the DAC in order to provide converting the digital information into an analog signal.

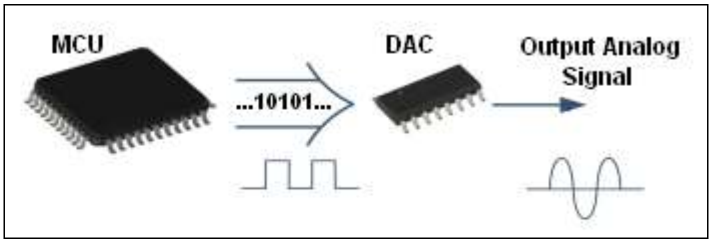

Figure. 7. Cascade of the Circuit for DA Conversion

Table 2. General Information for ADC Units

Type of ADC	Application	Devices and families	Main characteristics
Direct conversion (flash)	Precise and very fast signal processor.	MAX100 MAX104	Resolution 8 bits; Sampling rate up to 250Msps; High power consumption.
Pipeline	Fast signal processing; Precise power control.	MAX1200	Resolution 8 bits; Sampling rate up to 1Msps; Low power consumption.
Dual slope	Precision Analog Signal Processor; Precision Sensor Interface; High Accuracy DC Measurements.	TC5XX	Resolution 12 - 17 bits; Sampling rate up to 200ksps; Low power consumption.
Successive Approximation Register (SAR)	Data logging; Multi-zone Monitoring; Remote or Isolated Data Acquisition.	MCP30XX MCP32XX MCP33XX	The resolution 10 – 13 bits; Sampling rate up to 200ksps; Ultra low power consumption.
Delta-Sigma	Energy Metering and Power Measurement; Portable Instrumentation; Medical and Power Monitoring.	MCP34XX MCP35XX	The resolution 16 – 24 bits; Sampling rate up to 100ksps.

The DAC units find wide application in systems, which need to reproduce an analog signal out of stored digital information, therefore the DAC units are commonly used in music players to convert digital data streams into analog audio signals either used in televisions and mobile phones to convert digital video data into analog video signals, connected to the screen drivers to display monochrome or color images. The Digital-to-Analog cascade of the circuit that provides transferring and converting of digital information into an analog signal is illustrated in **Figure 7.** The suitability of DAC for a particular application is determined by following main parameters: power consumption, resolution, speed, accuracy, Total Harmonic Distortion (THD) and dynamic range.A resolution is a number of possible output levels, which DAC can reproduce. This is usually stated as the number of bits it uses, which is the base two logarithm of the number of levels. Resolution is related to the effective number of bits, which is a measurement of the actual resolution attained by the DAC. The resolution of a DAC place a crucial role in color depth in video and audio bit depth in audio applications.

The THD is a measurement of the distortion and noise, which are introduced to the signal by the DAC. It is expressed as a percentage of the total power of unwanted harmonic distortion and noise that accompanies the desired signal, as important DAC characteristic for dynamic and small-signal DAC applications. Dynamic range is a measurement of the difference between the largest and smallest signals the DAC can reproduce expressed in decibels, usually related to the resolution and noise floor. The described parameters are the most important and critical to be taken into consideration to assure required performance in a certain application, other characteristics such as speed, accuracy mostly depends on the type of ADC units. The application information and technical characteristics for most usable DAC devices are shown in **Table 3** [3, 7, 18 - 20].

5. Design of Digital Communication Bus

The digital data link or communication bus has a tangible advantage in contrast to an analog transmission line, that digital data doesn't degrade while being transmitted over long distances, whereas an analog signal can degrade and lose some information. The ADC units and DAC units that are listed in this article are featured with Inter Integrated-Circuit (I^2C) module or In System Programming (SPI) module.

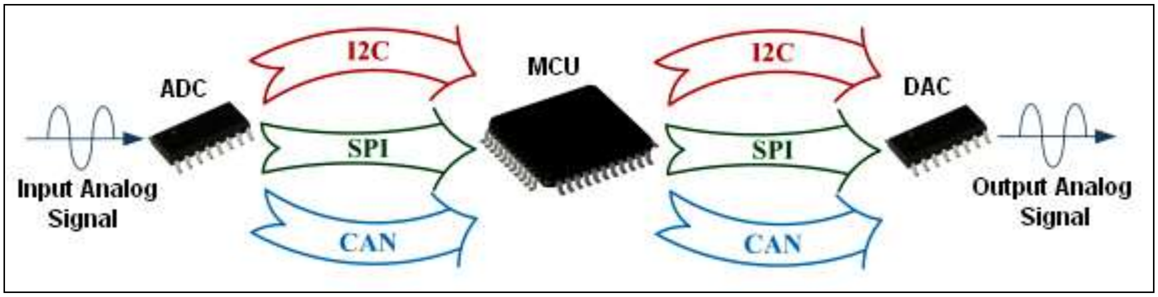

Figure. 8. Converting New Analog Signal

Table 3. General Information for DAC Units

Type	Applications	Devices and families	Main characteristics
Pulse-width modulator (PWM)	Precise voltage regulator; Motor speed controller;	MCP47XX; MCP48XX.	Resolution up to 12 bits; Low power consumption.
Delta sigma modulator	High quality audio conversion; Signal formers.	CS4390.	Resolution up to 24 bits Medium power consumption.
R-2R ladder	Voltage calibrator; Precise voltage regulator; Low quality audio.	MAX501.	Resolution up to 12 bits; Medium power consumption.

The I2C module for relatively slow or low conversion information capacity ADC units and DAC units is able to provide data transmission at 400kbit/s. The devices with relatively high conversion information capacity (such as for analog signal conversion) are featured with I^2C module, which is able to provide data transmission at 1M bit/s [4, 8, 21].

An important part of the digital-analog design, in which MCU and ADC or DAC as standalone units are used, is a digital communication bus between units. The digital communication bus can be Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI) and Control Area Network (CAN) (mostly used in automotive applications) through which the digitized analog data would go to the MCU for processing and after processing the digital signal would go to the DAC for converting into a new analog signal as shown in **Figure 8.**

The SPI module can provide much higher communication speed, which can be up to 10Mbit/s. Essentially the SPI module speed is determined by the clock of an MCU device. The CAN module is more specific in application. This CAN bus is designed for the network control onboard of a vehicle. In such a way, this module is usually embedded in ADC and DAC chips for automotive applications, nevertheless, they can be used in none automotive applications as well. Thus, the maximum data transmission speed of the CAN bus riches 1Mbit/s [9, 22, 23].

6. Benefits of Digital Conversion

The operation and description of the ADC and DAC stand-alone units can be very helpful and handy in contemporary analog designs. These devices are reasonable and have the best quality-price ratio and can be easily purchased for commercial and own projects. The concise and the brief narration of the ADC and DAC device characteristics, features and communication buses give a clear insight of benefits and advantages to be applied in an analog design. The benefits are the following:

1. The separate units of ADC and DAC allow assuring flexible design and layout of components on the printed circuit board, what gives more freedom to a designer (unless MCU doesn’t have embedded ADC or DAC or with incapable functionalities for a certain application);
2. Applying of stands alone ADC and DAC devices allow providing modernization of any microcontroller-based devices by adding external ADC or DAC chips;
3. The possibility of utilizing digital data transferring bus between MCU and ADC or DAC allows installation on the digital bus up to 255 devices, which can be maintained by a single MCU device; and
4. The wide variety of ADC and DAC devices allow selecting the most suitable device under conditions required by a certain application without exposing high requirements to the MCU, which simplifies designs significantly [7, 24, 25].

7. Conclusion

In recent years, several techniques, methods, and tools for designing low-power circuits have been presented in the scientific world. Thus, only a few of them have found their way in current design flows, so purpose of this work is to summarize, mainly by way of examples, what in the experience of researchers are the most trustful approaches to low power design. The contribution of this work should not be intended only as an exhaustive review of the existing literature on low-power design; rather, it analyses the existing technology and proposes insights that the designer can rely upon when power consumption is a critical constraint. In other words, this digital technology is focused solely on digital circuits with modest attention to CMOS and MOSFET devices, which is most widely adopted in current VLSI technique.

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