AN1072

Measuring VDD Using the 0.6V Reference

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INTRODUCTION

This application note describes how to measure the voltage supplied to a PIC® microcontroller, VDD. The device used in preparation of this application note was the PIC16F690.

The ability to measure VDD lends itself to battery applications where VDD is likely to fall over time. In this application note, an example program is provided with routines to measure VDD.

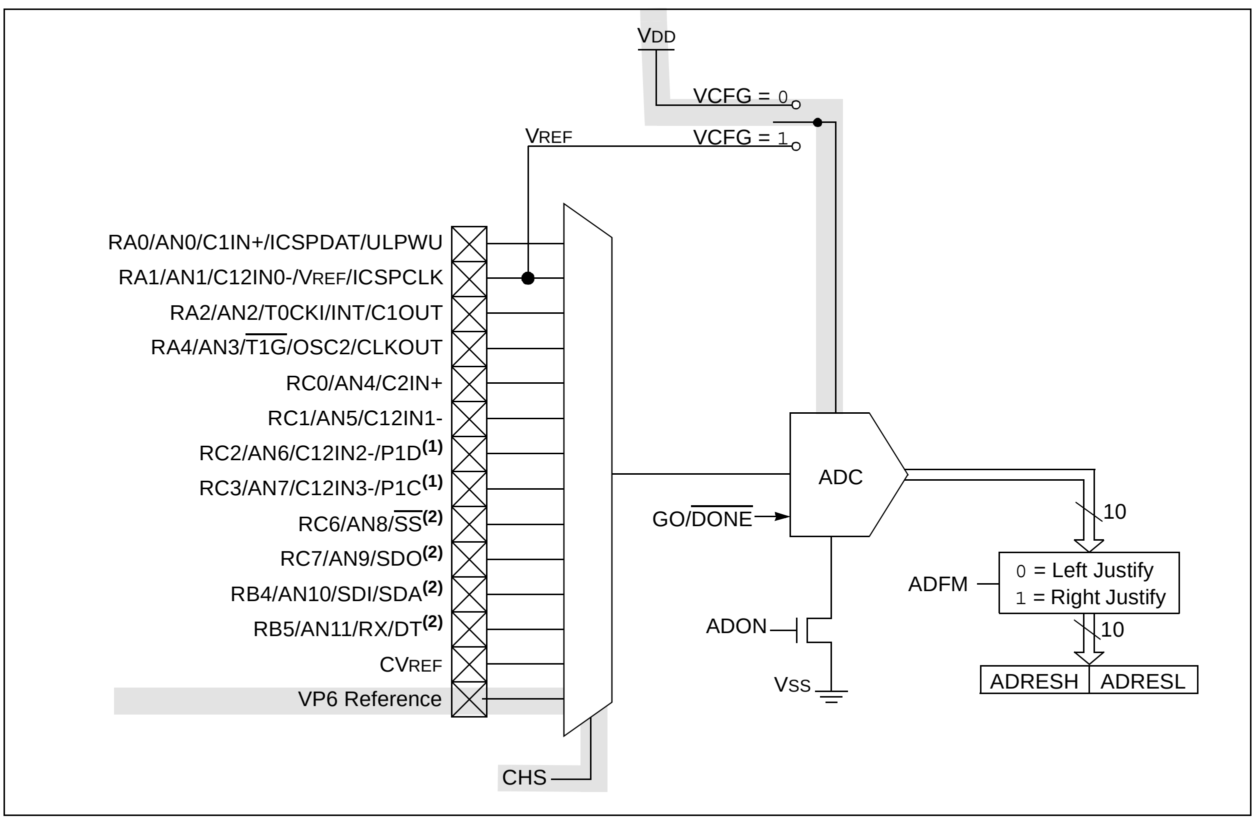
THEORY OF OPERATION

Select Microchip PIC microcontrollers contain a 0.6V or 1.2V internal reference that is selectable as an input to the ADC module. This provides a fixed reference to allow measurement of VDD. The PIC16F690 was chosen for this feature, although there are other capable devices. The ADC Block Diagram for the PIC16F690 is shown in Figure 1.

To measure VDD, VDD should be selected as the reference to the ADC via VCFG, and the 0.6V reference selected as the input using the channel select bits, CHS<3:0>. A measurement of the 0.6V input is taken with the ADC, and the result represents 0.6 Volts as a percentage of VDD. As VDD increases, the resulting number will decrease and vice versa. This yields a direct "1/x" relationship between VDD and the produced digital value as seen in Equation 1. In short, given a specific VDD, the digital value is always the same. Working backwards, if the digital value is known, VDD may be calculated.

The 0.6V input's ADC result may be expressed in 9 bits over all operating voltages and tolerances. So, when using the 10-bit ADC the result will be placed in the ADRESH and ADRESL registers with Right-Justification to treat the value as a 16-bit integer.

FIGURE 1: PIC16F690 ADC BLOCK DIAGRAM



Seen below, Equation 1 describes how an analog voltage is converted to a digital number. For the 10-bit ADC, n = 10. This formula was used to calculate the digital values for the table of **Appendix A: "ADC Results Table"**.

EQUATION 1:

$$VP6COUNT = 0.6V \frac{2^n - 1}{V_{DD}}$$

To convert a digital value back to an analog voltage is simple mathematically. Solve Equation 1 for V_{DD}, and the result is Equation 2.

EQUATION 2:

$$V_{DD} = 0.6V \frac{2^n - 1}{VP6COUNT}$$

These equations define the relationship between V_{DD} and VP6COUNT. The table in **Appendix A: "ADC Results Table"** lists the analog V_{DD} voltages and the corresponding digital value for 0.6V in the left two columns. The third column shows the analog value that the digital number actually represents after rounding (Equation 2). Once the ADC module is properly configured, taking a reading will produce the value VP6COUNT in ADRESH and ADRESL, and using the above relationship, V_{DD} can be calculated or action taken on the value.

IMPLEMENTATION

There are two considerations to keep in mind when attempting to measure and use the measurement of V_{DD}.

First, the ADC result is in counts, not in voltage. The relationship between counts and voltage is defined by Equations 1 and 2, and the values are tabulated in **Appendix A: "ADC Results Table"**.

Second, any variation of VP6 will shift the table, and the values will not represent the voltage expected. There is no way to know exactly what voltage the reference VP6 is before using the device. However, by performing a few calibrations, the value of the 0.6V reference can be removed from the measurement computation. This will greatly increase the accuracy over the straightforward approach of Equation 2. Simultaneously, it will yield values in the form of a 16-bit number as 480 for 4.80V for the useable output, which makes the use of measured values more convenient.

The cost to do this calibration is added complexity. To perform the calibration, a known and stable voltage V_{DD} must be applied, and then take a measurement of the 0.6V input. This value will be stored in the part's memory, and then used later when the voltage V_{DD} is unknown, call it Vu for unknown voltage at those times.This procedure for calibration and use is shown in Figure 2:

FIGURE 2: EQUATION DEVELOPMENT WITH DESCRIPTION AND EXAMPLE

Equation Development	Description	Example, VP6 = 0.59V, V_{REF} = 4.00
$VP6CALVAL = \frac{VP6}{V_{REF}} \bullet 1023$	Measure 0.6V with known voltage V_{REF}	$\frac{0.59V}{4.00V} \bullet 1023 = 150$
$VuCount = K \bullet VP6CALVAL\left(= \frac{VP6}{Vu} \bullet 1023\right)$	For unknown voltages, assume form Unknown Result = K * known CALVALUE (=ADC result)	For example, measure 5.38V. $VuCount = 112\left(= \frac{0.59}{5.38} \bullet 1023\right)$
$K \bullet \frac{VP6}{V_{REF}} \bullet 1023 = \frac{VP6}{Vu} \bullet 1023$	Substitute in 1st equation; set equal and solve for K	—
$K = \frac{V_{REF}}{Vu}$	Simplify to find K	—
$VuCount = \frac{V_{REF}}{Vu} \bullet VP6CALVAL$	Substitute K into assumed form	—
$Vu = \frac{(V_{REF} \bullet VP6CALVAL)}{VuCount}$	Solve for Vu. Known calibration values on top, and measured ADC result on bottom.	$Vu = \frac{(4.00 \bullet 150)}{112} = 5.35$
$Vu = \left(\left(\left(\frac{Vref \bullet 100}{2}\right) \bullet VP6CALVAL\right) / VuCount\right) \bullet 2$	Modify numbers for convenience of data storage V_{REF}*100 = 16-bit value for voltage Divide by 2, multiply by 2 avoids unnecessary 24-bit math.	$Vu = \frac{(400 \bullet 150)}{112} = (535)$ (as integer in microcontroller)

So, after taking a measurement of the unknown voltage VDD which produces ADC result VuCount, and knowing the VP6CALVAL taken during calibration with known VREF, the voltage may be found by the last two equations. The next to last equation is the mathematically proper equation, and the last equation is a form which makes the numbers more easily usable with 8 and 16-bit integer arithmetic.

Note:	The routines to calibrate and output data in the form of VDD * 100 are provided in the source code of this application.

USING THE SOFTWARE

Performing the Calibration

When to calibrate and where to store the calibration data is ultimately left to the end user's implementation. The provided source code was designed such that holding a button down while power is first applied will enter calibration mode, the calibration values are stored in EEPROM, and then normal program flow begins.

This calibration must be performed only once, since the value is stored in EEPROM. If the calibration value were stored in volatile memory, the calibration would need to be performed at least once each time the device became powered.

To perform the calibration with the supplied source code, there are two steps. First, when entering calibration mode, the device must be supplied proper voltage, and the voltage should be stored as a constant in program memory by the following line:

```
constant VREFPLUS = d'400'
```

A voltage of 4.00V is recommended for VDD during calibration when the full operating voltage of the part is to be used. If the part will only operate over a narrow range of voltage, calibrating the part in the middle of that range would be best, and the value above should be changed.

Once a voltage for calibration has been decided, the second step is to run the calibration routine. After supplying proper voltage as specified above, make the following call to store the calibration data to EEPROM.

```
call   StoreCalibData
```

The routine StoreCalibData takes a measurement of the 0.6V input and then stores the ADC value to the EEPROM within the device as described by the first equation of Figure 2. The calibration is now complete.

Measuring VDD With Software

When the device has proper values in the calibration registers, the software can be used by calling `MeasureVdd`. Two bytes will form the result in `Vdd_H` and `Vdd_L`. These two bytes are a 16-bit value of the form VDD * 100, and may be used for a trip point or to display the voltage. The 16-bit value is readily convertible to BCD formatting to display on an LCD for example.

ACCURACY

By calibrating the device, the maximum tolerance for error is reduced. The average value of the 0.6V reference is removed from calculations, and only its variation over temperature and voltage primarily affect any error in measurements. Round-off errors from using the ADC module always exist, but these errors are typically small in comparison.

Table 1 shows measurements taken for a single PIC16F690 for example purposes. This example shows why 4.00V was chosen for the VDD used to calibrate the device. Calibrating at 4V will cut the error due to voltage variation of the 0.6V reference roughly in half. This is seen by the negative error readings below 4 volts and positive error readings above 4 volts. It also puts an exact measurement on the calibration voltage.

TABLE 1: EXAMPLE CALIBRATED ACCURACY(1)

VDD Applied	MeasureVDD Output	% Error
2.50	248	-0.8%
2.75	272	-1.1%
3.00	298	-0.7%
3.25	324	-0.3%
3.50	348	-0.6%
3.75	374	-0.3%
4.00	400(2)	0.0%(2)
4.25	428	0.7%
4.50	452	0.4%
4.75	478	0.6%
5.00	506	1.2%
5.25	532	1.3%
5.50	556	1.1%

Mean Error 0.7%

Max Error 1.3%

Note 1: This example is not representative of all manufactured parts, and is used to illustrate the methods shown.

2: See Appendix B.

The variation of the 0.6V reference with respect to voltage does not have a specified tolerance, but a general characterization can still give an idea for expected tolerance. The following data are not specifications of the part, but are here to provide a general idea of the behavior.

For a given part, the absolute value of the 0.6V reference is ensured within the bounds specified by its data sheet. Given a specific part, the 0.6V reference will fluctuate as V_{DD} changes (e.g., 0.605V at V_{DD} = 2.0V, 0.595V at V_{DD} = 5.5V). The increase or decrease in the 0.6V reference above or below its value as measured during calibration will result in error in the measurement.

Table 2 shows rough values that can be expected for the range of voltage on the 0.6V reference. It shows these with differing degrees of confidence.

TABLE 2: 0.6V VARIATION OVER V_{DD}

Standard Deviation	% Devices Included	Typical Range (ΔV)
$\pm 1\sigma$	68.2%	14 mV
$\pm 3\sigma$	99.7%	19 mV
$\pm 6\sigma$	99.9%	28 mV

This data is a characterization from many PIC16F690 parts, but it is not a specification. It is very likely all devices' VP6 will vary across V_{DD} to within the maximum amount shown. For example, the voltage could change 28 mV from 0.650V to 0.622V over V_{DD} of 2 to 5.5V. **Appendix B: "Comparison of Calibrated Method versus Table Look-up Method for Same Part"** shows an example part with the confidence intervals applied to its mean as well as a comparison of the calibration routine versus using the ADC result alone.

In terms of the output of the calibrated V_{DD} measurement, this means that by using 4.00V to calibrate the device, the error is split roughly in half as shown earlier in Table 1. For the one standard deviation case, there will be about 7 mV above and 7 mV below the average 0.6V value for a tolerance of 1.2%. Table 3 shows each case.

TABLE 3: CALIBRATED RESULT TOLERANCES

Standard Deviation	Measured V_{DD} Estimated Tolerance
$\pm 1\sigma$	± 1.2%
$\pm 3\sigma$	± 1.6%
$\pm 6\sigma$	± 2.4%

Even using the largest tolerance for error with six standard deviations, the estimated tolerance of the calibrated output is roughly ±2.4% assuming a 0.6V average value. Compared to the direct method, where the tolerance of the 0.6V is the tolerance of the output, this is a great increase in accuracy.

CONCLUSIONS

Measuring V_{DD} can be used for a number of purposes such as system monitoring, low battery detection, or calibrating ADC measurements based on the true voltage.

V_{DD} may be measured with reasonable accuracy, and the user must perform only three actions with the source code to include it in a project. To summarize, the actions are below.

Ensure calibration voltage constant is correct

```
constant VREFPLUS = d'###'
```

Supply V_{REF} and run calibration

```
call StoreCalibValue
```

Issue call in main program

```
call MeasureVdd
```

Please see the related source code for the routines required to measure V_{DD}. An application using the PICkit™ 2 Low Pin Count Demo Board (DS51556) was used with an LCD to display V_{DD} along with other pertinent data such as the calibration value and the 10-bit ADC result, VuCount.

MEMORY USAGE

Memory usage for the minimal calibration and measurement routines are shown as "Cal & Meas." Memory usage for the example program which displays V_{DD} on an LCD is shown as "LCD Example."

TABLE 4: MEMORY USAGE

Program	Prog. Words	RAM Bytes	EEPROM
Cal & Meas	209	23	1
LCD Example	472	29	1

GLOSSARY OF TERMS

Acronym	Description
V_{DD}	Supply Voltage
VP6COUNT	ADC Output Value
VP6	Actual Voltage of 0.6V reference.
VP6CALVAL	ADC Value of VP6 at Calibration V_{DD}
Vu	Unknown Voltage
VuCount	Unknown ADC result
V_{REF}	V_{DD} used for Calibration

APPENDIX A: ADC RESULTS TABLE

Table provided for convenient look-up of ADC results given a VDD voltage under nominal conditions.

TABLE A-1: ADC RESULTS

VDD Applied	Digital 0.6V (VP6COUNT)	VDD Represented
2.50	245	2.50
2.52	243	2.52
2.54	241	2.54
2.56	239	2.56
2.58	237	2.59
2.60	235	2.61
2.62	233	2.63
2.64	232	2.64
2.66	230	2.67
2.68	228	2.69
2.70	227	2.70
2.72	225	2.72
2.74	223	2.75
2.76	222	2.76
2.78	220	2.79
2.80	218	2.81
2.82	217	2.82
2.84	215	2.85
2.86	214	2.86
2.88	212	2.89
2.90	211	2.91
2.92	209	2.93
2.94	208	2.95
2.96	207	2.96
2.98	205	2.99
3.00	204	3.00
3.02	202	3.03
3.04	201	3.05
3.06	200	3.07
3.08	199	3.08
3.10	197	3.11
3.12	196	3.13
3.14	195	3.14
3.16	193	3.18
3.18	192	3.19
3.20	191	3.21
3.22	190	3.23
3.24	189	3.24
3.26	188	3.26
3.28	186	3.30
3.30	185	3.31
3.32	184	3.33
3.34	183	3.35
3.36	182	3.37
3.38	181	3.39
3.40	180	3.41
3.42	179	3.42

VDD Applied	Digital 0.6V (VP6COUNT)	VDD Represented
3.44	178	3.44
3.46	177	3.46
3.48	176	3.48
3.50	175	3.50
3.52	174	3.52
3.54	173	3.54
3.56	172	3.56
3.58	171	3.58
3.60	170	3.61
3.62	169	3.63
3.64	168	3.65
3.66	167	3.67
3.68	166	3.69
3.70	165	3.72
3.72	164	3.74
3.74	163	3.76
3.76	163	3.76
3.78	162	3.78
3.80	161	3.81
3.82	160	3.83
3.84	159	3.86
3.86	158	3.88
3.88	157	3.90
3.90	157	3.90
3.92	156	3.93
3.94	155	3.95
3.96	154	3.98
3.98	154	3.98
4.00	153	4.01
4.02	152	4.03
4.04	151	4.06
4.06	150	4.09
4.08	150	4.09
4.10	149	4.11
4.12	148	4.14
4.14	148	4.14
4.16	147	4.17
4.18	146	4.20
4.20	145	4.23
4.22	145	4.23
4.24	144	4.26
4.26	143	4.29
4.28	143	4.29
4.30	142	4.32
4.32	141	4.35
4.34	141	4.35
4.36	140	4.38
4.38	139	4.41

VDD APPLIED	DIGITAL 0.6V (VP6COUNT)	VDD REPRESENTED
4.40	139	4.41
4.42	138	4.44
4.44	138	4.44
4.46	137	4.47
4.48	136	4.51
4.50	136	4.51
4.52	135	4.54
4.54	135	4.54
4.56	134	4.57
4.58	133	4.61
4.60	133	4.61
4.62	132	4.64
4.64	132	4.64
4.66	131	4.68
4.68	130	4.72
4.70	130	4.72
4.72	129	4.75
4.74	129	4.75
4.76	128	4.79
4.78	128	4.79
4.80	127	4.83
4.82	127	4.83
4.84	126	4.87
4.86	126	4.87
4.88	125	4.90
4.90	125	4.90
4.92	124	4.94
4.94	124	4.94
4.96	123	4.98
4.98	123	4.98
5.00	122	5.02
5.02	122	5.02
5.04	121	5.07
5.06	121	5.07
5.08	120	5.11
5.10	120	5.11
5.12	119	5.15
5.14	119	5.15
5.16	118	5.19
5.18	118	5.19
5.20	117	5.24
5.22	117	5.24
5.24	116	5.28
5.26	116	5.28
5.28	116	5.28
5.30	115	5.33
5.32	115	5.33
5.34	114	5.38
5.36	114	5.38
5.38	113	5.42
5.40	113	5.42
5.42	113	5.42

VDD APPLIED	DIGITAL 0.6V (VP6COUNT)	VDD REPRESENTED
5.44	112	5.47
5.46	112	5.47
5.48	111	5.52
5.50	111	5.52
5.52	111	5.52

APPENDIX B: COMPARISON OF CALIBRATED METHOD VERSUS TABLE LOOK-UP METHOD FOR SAME PART

Note: This example is not representative of all manufactured parts, and is used for illustrative purposes.

Measuring VDD on the same part with the two different methods

Calibrated Method			Table Look-up Method			(Both)
VDD Applied	**MeasureVdd Output**	**% Error**	**VP6COUNT**	**VDD of ADRES (Eq. 2)**	**% Error**	**Actual 0.6V**
2.50	248	-0.8%	245	2.51	0.2%	0.599
2.75	272	-1.1%	223	2.75	0.0%	0.599
3.00	298	-0.7%	203	3.02	0.8%	0.595
3.25	324	-0.3%	187	3.28	1.0%	0.594
3.50	348	-0.6%	174	3.53	0.8%	0.595
3.75	374	-0.3%	162	3.79	1.0%	0.594
4.00*	400*	0.0%*	152	4.04	1.0%	0.594
4.25	428	0.7%	142	4.32	1.7%	0.590
4.50	452	0.4%	134	4.58	1.8%	0.589
4.75	478	0.6%	127	4.83	1.7%	0.590
5.00	506	1.2%	120	5.12	2.3%	0.587
5.25	532	1.3%	114	5.38	2.6%	0.585
5.50	556	1.1%	109	5.63	2.4%	0.586

* Calibration voltage reads exact when operating under calibration conditions.

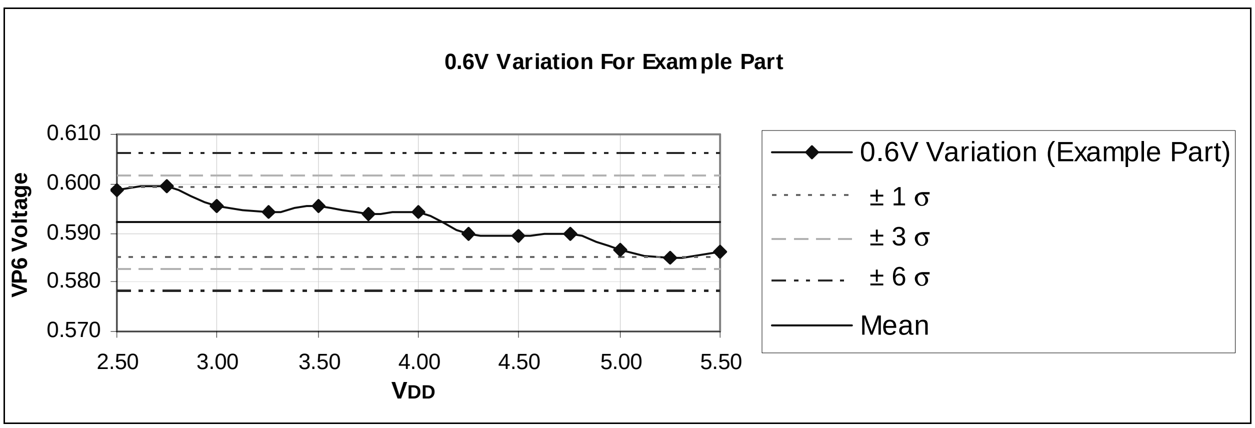
Mean Error 0.7%

Max Error 1.3%

Mean Error 1.3%

Max Error 2.6%

FIGURE 3: 0.6V VARIATION AND CONFIDENCE INTERVALS ON ΔV



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