

Application Note 226 Step-Up DC-DC Converter Calibration and Adjustment Using a Digital Potentiometer

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#### Introduction

The purpose of this application note is to show an example of how a digital potentiometer can be used in the feedback loop of a step-up DC-DC converter to provide calibration and/or adjustment of the output voltage. The example circuit uses a MAX5025 step-up DC-DC converter (capable of generating up to 36V, 120mW max) in conjunction with a DS1845, 256 position, *NV* digital potentiometer. For this example, the desired output voltage is 32V, which is generated from an input supply of 5V. The output voltage can be adjusted in 35mV increments (near 32V) and span a range wide enough to account for resistance, potentiometer and DC-DC converter tolerances (27.6V to 36.7V).

While the intent of this application note is to show an example of a step-up DC-DC converter, the ideas presented here can be applied to generate other combinations of output voltages, step sizes, ranges, and power requirements to meet your particular applications' needs. An additional application note is available (AN225) that shows an example of using a digital potentiometer with a step-down DC-DC converter. A link to AN225 appears at the end of this document.

#### Fixed Step-up DC-DC Converter

The typical circuit from the MAX5025 data sheet is shown in Figure 1. In this circuit, the output voltage,  $V_{OUT}$ , is determined by the ratio of fixed resistors R1 and R2. These two resistors form a voltage divider that feeds a fraction of the output voltage back to the FB pin, creating a closed-loop system. The system is at equilibrium when  $V_{OUT}$  is generating the desired output voltage and the R1 and R2 voltage divider feeds back 1.25V to the FB pin. When  $V_{OUT}$  is lower than the desired output voltage (and hence the voltage fed back to FB is below 1.25V), the DC-DC converter IC attempts to deliver additional power until FB reaches 1.25V. Equation 1 is directly from the MAX5025 data sheet. Solving Equation 1 for  $V_{OUT}$  yields Equation 2 where  $V_{REF}$ , the FB Set Point, is 1.25V for the MAX5025.

$$R1 = R2 \left(\frac{V_{OUT}}{V_{REF}} - 1\right)$$
Equation 1
$$V_{OUT} = V_{REF} \left(\frac{R1}{R2} + 1\right)$$
Equation 2

## Figure 1. Fixed Step-Up DC-DC Converter Circuit



## **Digital Potentiometer Considerations**

One possible way of adding a digital potentiometer into the feedback loop is shown in Figure 2. However, before selecting a digital potentiometer, a number of considerations must be given some thought. The following list of questions address important design considerations and assist in the device selection process.

- Is a 3V or 5V supply available for the potentiometer? The majority of digital potentiometers available require 3V or 5V to operate. Likewise, the voltage needs to be available before V<sub>OUT</sub> can be generated. Since the example circuit has a 5V input supply, this is not a concern here but if V<sub>IN</sub> were larger, this would be a major concern.
- 2. Will the system only be calibrated once? Or monitored/controlled closed loop? How will the digital potentiometer be controlled? Using a microcontroller? Push-button? *The answer to these questions will help select a specific digital potentiometer. For example, if the system is going to be calibrated once, say during production testing, then a NV (NV) potentiometer is needed to save the calibrated wiper position. Likewise, it is also important to consider how the potentiometer will be programmed. Will it be programmed with a production tester capable of talking 2-wire or 3-wire, or is a push-button potentiometer needed?*
- 3. How many steps are needed? What resolution is required? What range is needed? These answers determine the minimum acceptable number of potentiometer positions and serve as a benchmark when experimenting with different resistor values when finding a combination that is acceptable even in worst case conditions due to resistor/component tolerances. Furthermore, be aware that the desired output voltage range will be different than the actual output range so that the desired range can also be obtained even when using worst-case tolerances.
- 4. What is the max voltage that will ever be applied to the potentiometer terminals? Is  $V_{REF}$  ( $V_{FB}$ ) larger than the maximum allowable voltage on the  $V_W$  pin? Some potentiometers have a specification that states the maximum allowable voltage than can be applied to any of the potentiometer terminals. The second question is intended to be a sanity check. For example, the MAX5027 (not the MAX5025) has a  $V_{REF}$  of 30V! This voltage cannot be applied to the wiper terminal. The reason  $V_{REF}$  is so high is because it is a non-adjustable DC-DC converter.

- 5. Is the FB pin bias current large enough to cause a noticeable drop across the wiper resistance, R<sub>W</sub>? Does the FB pin bias current exceed the maximum (or abs max) wiper current specification? *Fortunately, the maximum wiper current specification is usually 1mA or larger, while the bias current is in the magnitude of nA. The second reason why the bias current is important is because if too large, the voltage drop across the wiper resistance becomes noticeable and should be accounted for when calculating the output voltage.*
- 6. Does the minimum and maximum position of the potentiometer connect directly to V<sub>L</sub> and V<sub>H</sub>? For example, the DS1805 is different in that the maximum potentiometer setting (255) does not connect directly to the H terminal. It is actually one resistor (LSB) away from the H terminal. Granted, the difference between 255 and 256 resistors are nil, the same is not the case for potentiometers with fewer positions. The result of this question can be seen later in Equation 4.
- What is the desired tolerance of V<sub>OUT</sub>? 5%? 10%? 3%? Keep in mind that the DC-DC converter IC itself has a tolerance. The MAX5025 for example has a tolerance of 5%. And this is completely independent from the tolerance of R1 and R2, which may also be 5% or 1%. These tolerances will be discussed in detail later.
- 8. What is the operating temperature range of the circuit? Just as important as knowing the effects of the tolerances, it is equally important to know the effects of temperature on the output voltage.

## Figure 2. Digital Potentiometer in the Voltage Divider Feedback Path



# Adding a Digital Potentiometer to the Feedback Path

Although there are several ways that a digital potentiometer could have been added to the circuit in Figure 1, this application note will only discuss the voltage divider configuration as shown in Figure 2. Two configurations that will not be discussed are 1) using the pot as a variable resistor (by connecting the wiper terminal to either the high or low terminal) between R1 and R2, and 2) eliminating R2 and connecting the pot low terminal to ground.

Equations 3, 4, and 5 show the relation of the potentiometers' position to  $R_L$ ,  $R_H$ , and  $R_{POT}$ . Once a potentiometer is added into the feedback loop, these equations can be used to modify Equations 1 and 2 to represent the new circuit.

$$R_{POT} = R_{H} + R_{L}$$
Equation 3  

$$R_{L} = current \ potentiometer \ position \times \left(\frac{R_{POT}}{(total \ number \ of \ pot \ positions - 1)}\right)$$
Equation 4  

$$R_{H} = R_{POT} - R_{L}$$
Equation 5

 $R_{POT}$  is the end-to-end resistance of the potentiometer and  $R_H$  and  $R_L$  are dependent on the current wiper position setting (see Figure 2). The denominator of Equation 4 is *(total number of pot positions -1)* if the max and min wiper positions connect directly to the H and L potentiometer terminals, which is true for the DS1845. Some digital potentiometers may have an additional resistor between the max potentiometer setting and the H terminal. The denominator for those potentiometers would not include the -1 and simply be *(total number of pot positions)*.

Equation 2 becomes,

$$V_{OUT} = V_{REF} \left( \frac{R1 + R_{H}}{R2 + R_{L}} + 1 \right)$$
 Equation 6

#### **Resistor Calculations**

Unfortunately, there is no quick, easy way of calculating R1 and R2.  $V_{OUT}$  is a function of multiple variables and many solutions exist. Choosing the optimal solution for a particular application involves a decent amount of trial and error. For this reason, a spreadsheet is the single most valuable tool because it allows the designer to make a tweak and instantly see its effects on  $V_{OUT}$  for a single potentiometer position as well as a sweep of the entire potentiometer range. The following will describe the process used to calculate the values for the example circuit generating 32V.

Assumptions made up front for this design were,  $R_{POT} = 10k\Omega$ , 256 positions,  $V_{REF} = V_{FB} = 1.25V$ , and the output voltage will be 32V when the pot is set in the middle position (position 127). The spreadsheet created for this application note can be found on the Dallas Semiconductor ftp site. A link to the spreadsheet can be found at the end of this application note. Plugging the assumptions into Equations 4 and 5, and then into Equation 6 determines the needed ratio between R1 and R2.

$$\frac{V_{OUT}}{V_{REF}} - 1 = \left(\frac{R1 + 5019.6}{R2 + 4980.4}\right) = \frac{32}{1.25} - 1 = 24.6$$
 Equation 7

The MAX5025 data sheet says to choose an R2 in the  $5k\Omega$  to  $50k\Omega$  range and then calculate R1. However, how can one make an educated R2 selection in such a large range without knowing what else will be effected? The spreadsheet shown in Figure 3 was created specifically for this. Simply type in a value for R2 in the red cell (D7). R1 is then automatically calculated to obtain the ratio in cell Q7 (which was the result of Equation 7). In addition, thousands of other calculations are also performed and then V<sub>OUT</sub> vs. Pot Position is plotted. The V<sub>OUT</sub> vs. Pot Position plot shows the expected output voltage for all 256 potentiometer positions. Linearity, range, and slope can all be seen clearly. Look for the trace labeled "Typical". The other traces will be described later. Comparing plots of R2 =  $5k\Omega$  and R2 =  $50k\Omega$  (Figure 4) it can be seen that smaller values of R2 (Figure 4a) produce a much larger output range, although non-linear and having a steep slope. The steep slope produces larger than desired step sizes (especially at the lower potentiometer positions)

decreasing the resolution of  $V_{OUT}$ . Larger values of R2, on the other hand, produce a linear output and much smaller slope (Figure 4b). The smaller the slope, the smaller the step size (and hence resolution). When attempting to "fine-tune" a particular output voltage, it is desirable to have many potentiometer positions at and around the desired output voltage. The drawback, which will be discussed in the following section, is that since R1 and R2 have a tolerance of ±1%, there is a possibility that no potentiometer setting will reach 32V. This can be seen looking at the top trace in Figure 4b. When the potentiometer is set to position 0, the output voltage is ~37.5V and when the potentiometer is set to position 255, the output only goes down to 32.3V. Therefore, it is important to find a happy medium. For the example circuit, the happy medium (determined by trial and error, entering various values of R2 and looking at the V<sub>OUT</sub> vs. Pot Position graph ensuring that 32V could be reached in all conditions with an acceptable step size) is 30k $\Omega$ . The closest 1% SMT standard value is 30.1k $\Omega$ . Plugging this value into the spreadsheet and having it recalculate R1, the closest standard value had to be found for R1 as well. The graph shown in Figure 3 shows that 32V can be obtained even in the worst-case conditions.

	A	в	С	D	E	F	G	н		J	K	L	M	N	0	P	Q	B	S
1																			
2	Set Ext R2																		
3			B1 and B2	are standar	d 1% values												Position fo	r 32V	
đ						1											127	4920 292	
- T			1	•/						Eut D1 F	(1=/)	Ent DO Ent	- (1+/)	Dat (and to	and Denie		121	4000.002	
0			' '	×.						EXCHIE	nor (1%)	Ext R2 Erro	ər(1%)	Pot lena to	o enaj Resis	tance			
6	potpos	pot value	Ext R1	Ext R2		Vref (min)	Vref (typ)	Vref (max)		Min	Max	Min	Max	Min	Max		R1/R2 ratio	so 7Fh = 32	27
- 7	256	10000	845000	30100		1.19	1.25	1.31		836550	853450	29799	30401	8000	12000		24.6		
8			738000	30000	ratio lo	ratio lo	ratio high	ratio high			Delta between	pot positio	าร			Volta	ge on high si	ide of pot	
9	pot pos	BL	Vout (tup)	pot %	pot min	pot max	pot min	pot max	tup		r lo, p min	r lo, p max	r hi, p min	r hi, p max	tup	r lo, p min	rlo, p max	r hi, p min	r hi.p max
10	0	0	36 75664	0	34 2486	34 40517	39 18038	39,35623							1.665282	1503148	1.659721	1.66169	1.837534481
11	1	29.21569	26 70992	0.002922	24 21229	24.252	29 12919	29 294 17	.0.047926		.0.025206675	.0.052175	-0.041206	-0.062054	1.662116	1 50 1 599	1657156	1659942	1.924627207
10		70 40107	00.10002	0.003022	04.17000	24,20000	20,00000	00.20411	-0.047020		-0.035300013	0.050011	-0.041200	0.002004	1.000110	1.501050	1.051150	1.050342	1.004001201
12	2	10.43131	36.66112	0.007843	34.17606	34.23633	33.03806	33.23231	-0.047702		-0.035233855	-0.053011	-0.041113	-0.061858	1.660304	1.500052	1.604033	1.656136	1.831743055
13	3	117.6471	36.61354	0.011765	34,1429	34.24614	39.05702	39,17065	-0.047578		-0.03516146	-0.052847	-0.041033	-0.061664	1.658799	1.498508	1.65205	1.656458	1.828869982
14	4	156.8627	36,56608	0.015686	34.10781	34,19346	39.01608	39,10918	-0.047455		-0.035089188	-0.052685	-0.040947	-0.06147	1.656649	1.496968	1.649508	1.654721	1.825999945
15	5	196.0784	36.51875	0.019608	34.07279	34.14093	38.97521	39.0479	-0.047332		-0.035017138	-0.052523	-0.040861	-0.061278	1.654505	1.495431	1.646974	1.652988	1.823138902
16	6	235.2941	36.47154	0.023529	34.03785	34.08857	38.93444	38,98682	-0.047209	1									1.82028681
17	7	274.5098	36.42446	0.027451	34.00297	34.03637	38.89375	38.92592	-0.047087										1.817443629
18	8	313.7255	36.37749	0.031373	33,96817	33,98433	38.85314	38.86522	-0.046966				¥	vs. PUT	PUSITION	4			1.814609315
19	9	352.9412	36,33065	0.035294	33,93344	33,93245	38,81262	38,8047	-0.046845										1.811783827
20	10	392 1569	36 28392	0.039216	22,99979	33 88072	38 77219	39 74437	.0.046725		<b>C</b> 1 1 1	1							1 808967125
21	11	421 2725	2020002	0.042127	22.00410	22 02015	20 72102	20 60422	0.040020		Chart Area								1 906159167
21	10	431.3720	30.23732	0.043137	00.000410	00 22224	30.73103	30.00423	-0.040604		40					<ul> <li>Typical</li> </ul>			1.000103107
22	12	470.5882	36,19083	0.047059	33.82367	33.11114	38,63107	38.62428	-0.046480		40					Batio M	lin/ Pot Mir		1.803359913
23	13	509.8039	36,14447	0.05098	33,79522	33.72649	38.65138	38,56451	-0.046366		39 🥾					Devie M			1.800569322
24	14	549.0196	36.09822	0.054902	33,76084	33.67539	38.61128	38,50492	-0.046247							- Hatio M	inneot ivia		1.797787355
25	15	588.2353	36.05209	0.058824	33,72653	33.62445	38.57126	38.44552	-0.046129		38 🕂			++++		🗕 🗕 🛏 🛏 🗧	lax/Pot Mit	-	1.795013971
26	16	627.451	36.00608	0.062745	33,6923	33.57366	38,53133	38.38631	-0.046011							🗶 Ratio M	lax/Pot Ma		1.79224913
27	17	666.6667	35,96018	0.066667	33,65813	33.52302	38.49147	38.32727	-0.045894		37 📘			++++	++++			1	1.789492794
28	18	705.8824	35.91441	0.070588	33.62403	33.47253	38.4517	38.26842	-0.045777							R1 = 84	5k (1%), 📲		1.786744923
29	19	745.098	35.86875	0.07451	33,58999	33.4222	38.41201	38,20974	-0.045661		30 11					R2 = 30	.1k (1%), 📲	1	1.784005477
30	20	784.3137	35.8232	0.078431	33,55603	33.37202	38.37241	38,15125	-0.045545		35					POT = 1	10k (20%), 📘		1.78127442
31	21	823 5294	35 77777	0.082353	33 522 14	33 32 199	38 33288	38 09294	-0.045429			Тур	ical			Vrp = 1.2	257 (5%)		1778551711
22	22	962 7451	25 72246	0.096275	22 40021	22 27211	20 20244	29.0249	.0.045214		- 34 <del>}</del>	JIH							1 775927212
- 02	22	002.1401	05.10240	0.000213	00.45450	00.21211	00.20044	07.07004	-0.045314		2 1								1.770101107
33	23	301.3606	30.00720	0.030136	33,40406	33.22237	36.25406	37.37504	-0.045133		🚡 33 🕂	+ • + +			++++		++++	-	1.773131107
34	24	341.1765	35.64217	0.094118	33.42087	33.17279	38.2148	37.91906	-0.045085		- S 📕								1.770433297
35	25	980.3922	35.5972	0.098039	33.38724	33.12335	38.17559	37.86145	-0.044972		- 32							1	1.767743604
36	26	1019.608	35.55234	0.101961	33,35369	33.07406	38,13647	37.80402	-0.044858										1.765062071
37	27	1058.824	35.5076	0.105882	33.3202	33.02492	38.09743	37.74676	-0.044745		31 <b>1</b>								1.762388661
38	28	1098.039	35.46297	0.109804	33,28678	32.97592	38.05847	37.68967	-0.044633		30 🕂								1.759723337
- 39	29	1137.255	35.41845	0.113725	33,25343	32.92707	38.01959	37.63276	-0.044521		~~ []								1.757066063
40	30	1176.471	35.37404	0.117647	33.22015	32.87837	37.98079	37.57602	-0.044409		29 🕂		++++	++++					1.754416802
41	31	1215.686	35.32974	0.121569	33,18693	32.8298	37.94207	37.51944	-0.044298										1.751775518
42	32	1254,902	35,28555	0.12549	33,15377	32,78138	37,90342	37,46304	-0.044187		28 🕂						177	<u> </u>	1,749142175
43	22	1294 119	35 24 147	0 129412	33 12069	32 7221	37 86486	37 40681	-0.044077										1746516737
4.6	24	1222 222	25 19751	0.123222	22.09767	22 69497	37,82627	27 25025	.0.043967		21 🛨								1743899169
45		1070 540	00.10701 05.15005	0.100000	00.00107	02.00407	37.02037	07.00405	0.040057		26								1 741000405
40	35	1372.948	30,10365	0.137255	33.05471	32.63697	37.78796	37.23485	-0.043857		20 1								1.791283935
46	36	1411.765	35,1099	0.141176	33.02182	32.58912	37.74963	37.23913	-0.043748		25								1.7386875
47	37	1450.98	35.06626	0.145098	32.989	32.54141	37.71138	37,18356	-0.043639						450			, I	1.73609333
48	38	1490.196	35.02273	0.14902	32.95624	32.49383	37.6732	37.12817	-0.043531		U	50		100	150	200	250	,	1.733506889
49	39	1529.412	34.97931	0.152941	32,92355	32.4464	37.63511	37.07294	-0.043423				Pr	T POSITI	ON (DEC)				1.730928144
50	40	1568.627	34.93599	0.156863	32.89092	32,3991	37.59708	37.01787	-0.043315										1.728357059
E 1	4.4	1007.040	24.00070	0.100704	22.05025	00.05104	07 EE014	20.00207	0.040000										1 705 700001

### Figure 3. Example Resistor and Error Spreadsheet Screenshot

Once values for R1 and R2 are selected, it is important to verify that  $V_H$  does not exceed the maximum specification (of  $V_{CC} + 0.5V$  for the DS1845).  $V_H$  can be calculated using Equation 8.

$$V_{\rm H} = \frac{V_{\rm OUT}}{\left(R1 + R2 + R_{\rm POT}\right)} \times \left(R2 + R_{\rm POT}\right)$$
Equation 8

Figure 5 shows a screenshot of the bottom of the example spreadsheet. The calculation of  $V_H$  can be seen on the far right along with the max voltage across the potentiometer. We can see that for the resistor values we chose  $V_H$  has a worst case potential of 1.84V. This voltage is well within the recommended operating conditions. Other items in interest in Figure 5 are  $V_{OUT}$  min/max, min/max deltas between pot positions, and also min/max  $V_H$ . While some of the data and calculations shown in the spreadsheet may appear to be of little use, it provides multiple sanity checks to ensure a good design.

### Figure 4. R2 Comparison



#### **Figure 5. Additional Calculations**

262	252	9882.353	27.67158	0.988235	27.18028	24.7505	30.96512	28,1526	-0.027168		-0.022278334	-0.027592	-0.025786	-0.031839	1.253678	1.192924	1.193975	1.31327	1.31443953		
263	253	9921.569	27.64447	0.992157	27.15804	24.72297	30.93938	28,12084	-0.027114		-0.022241873	-0.02753	-0.025743	-0.031767	1.25245	1.191948	1.192647	1.312178	1.312956347		
264	254	9960.784	27.61741	0.996078	27.13583	24.6955	30.91368	28.08914	-0.027061		-0.022205501	-0.027469	-0.025701	-0.031695	1.251224	1.190973	1.191322	1.311088	1.311476508		
265	255	10000	27.5904	1	27.11366	24.66809	30.88802	28.05752	-0.027008		-0.022169218	-0.027408	-0.025658	-0.031624	1.25	1.19	1.19	1.31	1.31		
266																					
267			Vout	min	27.11366	24.66809	30.88802	28.05752	-0.047826	delta bet	-0.02765228	-0.037243	-0.032123	-0.043177	1.665282	1.503148	1.659721	1.66169	1.837534481	<- max Vh	
268				max	34.2486	34.40517	39.18038	39.35623	-0.027008	%(32V)	-0.086413374	-0.116386	-0.100385	-0.13493	0.415282	0.313148	0.469721	0.35169	0.527534481	<- max volta	ge across pot
269																			6.59418E-05	<- max end-t	o-end current

### **Error Analysis**

Up to this point, all calculations have used typical (nominal) values. However, to ensure the design is production worthy it is essential to calculate the variations of the output voltage due to component tolerances, temperature variations, and any other sources of error and ensure that the desired output voltage can always be obtained. This application note will go as far as analyzing the effects of resistor, potentiometer, and  $V_{REF}$  tolerances. The analysis of temperature variations, however, is saved for a future application note.

The MAX5025  $V_{REF}$  has a tolerance of ±5%. This means that the 1.25V could actually be anywhere between 1.19V and 1.31V. What makes this tolerance different than that of the resistors and potentiometer is that this 5% is for the entire temperature range. The resistors and potentiometer on the other hand spec both a tolerance and a temperature coefficient. Resistors R1 and R2 both have a tolerance of ±1%. The tolerance of the DS1845 is ±20%.

Referring back to Figure 3, the use of these tolerances can be seen in row 7 of the spreadsheet. For example, C7 is the nominal value of R1, while J7 is nominal (C7) minus 1% and K7 is the nominal plus 1%. Once this is done for all of the tolerances, calculations can easily be repeated multiple times, calculating all possible combinations in search of the combinations that yield the minimum and maximum output voltages. These combinations can then be added to the  $V_{OUT}$  vs. Pot Position plot and verified that each can generate 32V. Once all of the traces on  $V_{OUT}$  vs. Pot Position graph meets the desired specifications, the resistor selection is complete. Figure 6 shows the final circuit with the DS1845 and with the selected values of R1 and R2. The  $V_{OUT}$  vs. Pot Position plot for this circuit is shown in Figure 3.



### Figure 6. Final Circuit Using a DS1845 Digital Potentiometer

## Conclusion

This application note shows an example of how to use a digital potentiometer in the feedback loop of a stepup DC-DC converter to allow the output voltage to be calibrated. While this application note specifically uses the MAX5025 and the DS1845 to generate 32V, the concepts presented here can be applied towards other potentiometer/converter combinations as well as other output voltages and power ratings.

Questions/comments/suggestions concerning this application note can be sent to: MixedSignal.Apps@dalsemi.com.

Link to the spreadsheet used in this example: <u>ftp.dalsemi.com/pub/system\_extension/pots/AN226/AN226.xls</u>

Link to Application Note 225 showing a step-down DC-DC converter: <u>http://pdfserv.maxim-ic.com/arpdf/AppNotes/app225.pdf</u>

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