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Configurable ICs Build Versatile, Low-Cost Regulated Charge Pumps

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Many battery-powered applications in the IoT market require additional voltage levels for powering specific interface circuits, sensors, etc. Under certain operating conditions, charge pumps (also known as switched capacitor converters) provide simple, efficient solutions for generating the required supply voltages. While standalone charge pump ICs can be used, charge pumps can also be implemented using a GreenPAK configurable mixed-signal IC (CMIC).

When compared with designs based on standalone charge pump ICs, a GreenPAK charge pump design offers several advantages. These include lower cost, smaller size, multiple outputs with the same IC, programmable operating frequency, control via a serial interface, lower quiescent current, and on-chip logic for additional functions. In general, the advantage of the GreenPAK solution is its flexibility to shift the design to meet system priorities such as a focus on power consumption, output ripple, or other parameters.

This article explains how to design regulated capacitive charge pumps using a GreenPAK CMIC and a few low-cost external components. A single-stage charge pump may be configured as a voltage booster or voltage inverter. Multistage charge pumps enable higher output voltages, both positive and negative (inverting doubler, tripler, etc). The output is a regulated voltage source, independent of input voltage level variations and load variations, provided that input voltage and load are within defined limits.

The GreenPAK-based charge pump operates at input voltages of 1.8 V to 5 V and load currents up to 145 mA. Overall performance (a combination of power efficiency, voltage efficiency, output ripple, quiescent current, EMI and other factors) peaks at input voltages of 3 V to 5 V and output currents of 1 mA to 5 mA, using external Schottky diodes.

One GreenPAK CMIC can control multiple charge pumps with various output voltages. Independent programmability may be limited to some of the outputs, depending on the GreenPAK part selected. In the case of low input voltages, GreenPAKs may be cascaded to obtain higher output voltages with fewer external components than non-cascaded, multistage charge pumps. Links to the design files required to implement the charge pumps described in this article are provided in the reference section.[1-4] Also, note that these regulated charge pump designs are extensions of unregulated designs described previously in a Dialog Semiconductor application note.[5]

Charge Pump Circuit Design

The GreenPAK power supply voltage is used as the charge pump input. The GreenPAK outputs a driving signal for the external bootstrap capacitor. For multistage charge pumps, the GreenPAK outputs two anti-phase driving signals.

A control signal is optional to start/stop (power down) the charge pump and can be added as an IO or through serial communication protocols. When using I^{2}C-enabled GreenPAKs the output-voltage level can be programmed by controlling the internal reference voltage over I^{2}C communication. If tight output voltage tolerance is required, an external precision reference may be applied.

Simplified schematics of two single-stage charge pump regulators based on GreenPAK devices are shown in Fig. 1.

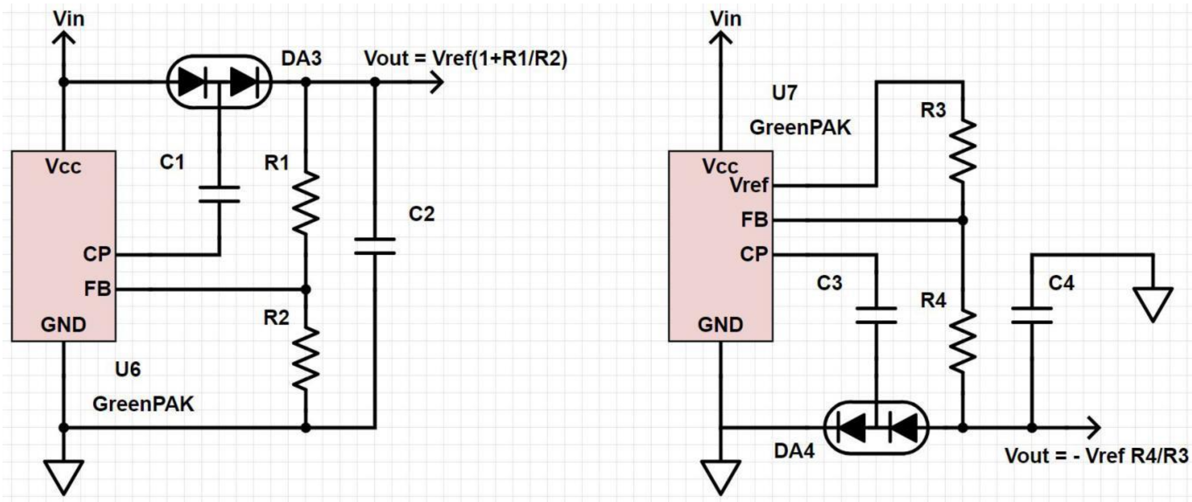


Fig. 1. Single-stage charge-pump-regulated voltage booster (left) and inverter (right).

As previously noted, the implementation of the regulated GreenPAK charge pump designs described in this article are based on an unregulated charge pump design.[5] A comparator is added to detect when the desired output voltage is met and then stop charging the output capacitor. In this way the output voltage is limited without adding an LDO or other type of dissipative regulator. Since analog comparators are available on-chip in most GreenPAKs, the only additional circuitry needed is a resistive voltage divider.

Regarding the charge pump performance, the procedure for designing a regulated charge pump is similar to the procedure for designing an unregulated charge pump. A designer needs to make sure that charge pump in the unregulated configuration can provide high enough output voltage under all working conditions (input voltage and load current). The feedback introduced by the voltage divider will regulate the output voltage. The necessary voltage margin is negligible. Here, voltage margin refers to the difference between the output voltage of an unregulated charge pump and the maximum output voltage of a regulated charge pump.

Operating Frequency And Capacitor Selection

Operating frequency and capacitor selection are explained in the application note for unregulated charge pumps;[5] these principles all apply to regulated charge pumps too. Additionally, we will examine how operating frequency and capacitance affects output voltage regulation.

Output voltage regulation is achieved by controlling the peak output voltage value, so the average value of output voltage depends on the ripple. At no load, ripple is zero, so average voltage equals peak voltage. At full load, the ripple at maximum, and average value is the peak value minus half of the peak-to-peak ripple. Regulation "zero to full load" equals half of the maximum peak-to-peak ripple.

Ripple depends on load, operating frequency and capacitance. Load cannot typically be altered by design, but operating frequency and capacitance can be set for correct operation.

Increasing operating frequency reduces ripple and improves output voltage regulation. However, it also increases power losses and reduces efficiency. Increasing output capacitance reduces ripple and improves output voltage regulation. However, bigger capacitors are usually larger in size and higher in cost.

Note that a bigger output capacitor also means a longer startup time, as well as a longer transition time between regulated output voltages. At light loads and large output capacitance a transition to a lower voltage level might take a very long time.

For top efficiency, improve regulation by increasing the output capacitance. For low price, low size, and fast response, improve regulation by increasing the operating frequency.

Diode Selection

Diode selection is also explained in the application note.[5] However, regulated charge pumps lack the influence of diode forward voltage to output regulation, so diodes only affect the maximum achievable output voltage. After regulation is introduced, diodes will only marginally affect the power efficiency, provided the circuit is "in regulation".

Efficiency will not be much higher if diodes with lower forward voltage drop (such as schottky diodes) are applied, but the dissipation will shift from the diodes to the GreenPAK chip itself. In certain applications standard diodes with higher forward voltage drop may help reduce the heat produced by the GreenPAK IC.

Feedback Design For The Voltage Booster

Feedback design is simple for the case of the voltage doubler. The output voltage peak is directly determined by the resistive divider ratio and the reference voltage is provided by the GreenPAK's internal blocks. Reference voltage performance is best around 1 V, which is also a handy value for calculations. The divider ratio to obtain V_{out} at V_{ref} is

$$R_1/R_2 = V_{out}/V_{ref} - 1$$

Using V_{ref} = 1 V gives $R_1/R_2 = V_{out} - 1$. For example, V_{out} = 5 V and V_{ref} = 1 V, $R_1/R_2 = 4$.

Regarding the resistance of the divider, an easy approach is to make divider current 1% of the maximum output current.

$$V_{ref}/R_2 = I_{outmax} * 1\%$$

For example, I_{outmax} = 1 mA, R_2 = 1 V/10 µA = 100 kΩ and $R_1 = 4 * R_2$ = 400 kΩ.

A resistive divider loads the charge pump and increases quiescent current thus reducing the circuit efficiency. Therefore, it's better to aim for high resistance. However, too high a resistance makes the circuit susceptible to electromagnetic interference and introduces noise that reflects to the output voltage. Additionally, the input characteristics of a GreenPAK comparator at high divider resistance become less negligible and may affect output voltage regulation.

The comparator input impedance is very high at a gain of 1x, but much lower when using an internal divider as documented in Table 1.

Table 1. Analog comparator input characteristics.

Gain	1x	0.5x		0.33x		0.25x	
Input resistance	100 MΩ	1 MΩ	2 MΩ	0.8 MΩ	2 MΩ	1 MΩ	2 MΩ
Input current at 1 V	10 nA	1 µA	0.5 µA	1.25 µA	0.5 µA	1 µA	0.5 µA

With the GreenPAK's internal divider on, input current is around 1 µA. To keep it below 1%, divider current should be at least 100 µA, which is too high for low-power applications. It is better to use the comparator with the divider switched off, when input current is around 10 nA and it is below 1% for divider currents of 1 µA and above.

Leakage current is 1 nA typical, making it 10 times less than the comparator input current. However, leakage current is strongly dependent on temperature and may reach 1 µA at high temperatures. Charge pump losses heat up the GreenPAK CMIC and temperature may rise considerably even at moderate ambient temperatures. For most applications, leakage current will stay below 0.1 µA; still 10x higher than comparator input current. To keep the error below 1%, divider current should be at least 10 µA.

Recommendation: design divider current to be 10 µA or more, except in the case the GreenPAK operates in high ambient temperatures or in the case of a high-power charge pump (high losses) when a 100-µA divider current is the preferred option.

Feedback Design For The Voltage Inverter

In the voltage inverter circuit, an output voltage divider referred to ground yields a sense voltage below ground —outside the GreenPAK supply voltage range. Such a sense signal cannot be applied to the comparator input, so a voltage divider must be biased to a reference potential above ground. One solution is to take advantage of the GreenPAK internal reference wired to an output pin. In this configuration, the circuit works with two reference voltages, one reference used for comparator threshold (call it "threshold voltage") and the other reference used for feedback (call it "reference voltage").

Output voltage peak value is determined by the ratio of resistive divider and the difference between reference voltage and threshold voltage and referred to reference voltage.

$V_{out} = V_{th} - R_f(V_{ref} - V_{th})/R_r = V_{th}(1 + R_f/R_r) - V_{ref} * R_f/R_r$

Programming the GreenPAK's internal references V_{ref} and V_{th} sets the output voltage level, with fixed voltage divider ratio.

Taking $V_{th} \sim 0$, greatly simplifies the expression for output voltage:

$V_{out} \sim -V_{ref} * R_f/R_r$

When considering voltage divider resistance in the case of a voltage inverter, the designer must consider the current capacity of the GreenPAK reference output. Current capacity is relatively low and resistance must be high enough to avoid overload.

Feedback Design For An Input-Referenced Inverter

In the common case when input voltage is regulated (tight tolerance) and it's satisfactory for the output voltage regulation to match input voltage regulation, the input voltage may be used to generate a reference voltage. In this case, the circuit is simplified and resembles the voltage doubler configuration (see Fig. 2).

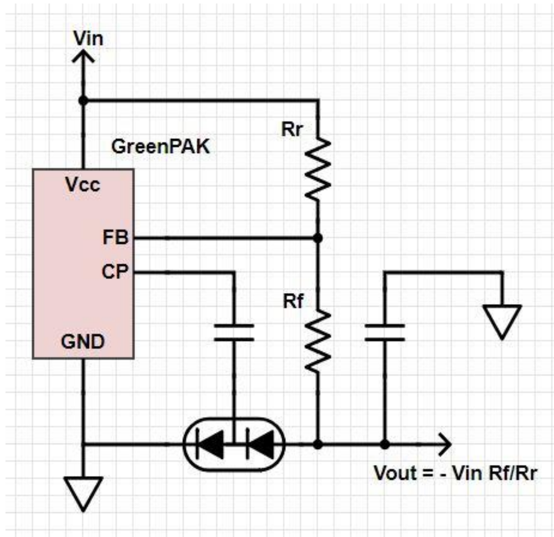


Fig. 2. An input-referenced regulated inverter.

Replacing the reference voltage with the input voltage gives the formula for output voltage:

$V_{out} = V_{th} - R_f (V_{in} - V_{th})/R_r = V_{th}(1 + R_f/R_r) - V_{in} * R_f/R_r$

Programming V_{th} sets the negative output voltage.

Choosing $V_{th} \sim 0$, greatly simplifies the expression for output voltage:

$V_{out} \sim -V_{in} * R_f /R_r$

For a single-stage voltage inverter, R_f must be less than R_r, because the absolute value of the output voltage cannot be higher than the input voltage.

The same principles that apply for choosing resistor values for the voltage doubler also apply to the inverter configuration.

Configuring The Chip

The GreenPAK design adds one analog comparator and a couple of gates to the unregulated charge pump design. Operating frequency affects regulation, since feedback controls the output peak value rather than the average level, so output voltage declines with rising output ripple. Keeping output ripple low by selecting a high operating frequency and/or large output capacitor improves output voltage regulation.

Oscillator Design And Output Pin Design

Oscillator and output pin design are explained in the application note.[5] However, the voltage drop introduced by an output pin's serial resistance is neutralized by regulation, so output pin configuration only affects maximum output voltage. Output pin configuration still affects efficiency as with an unregulated charge pump. Efficiency will be better if pins with lower resistance are used, if multiple pins are wired in parallel, and also if a GreenPAK with better IO performance is selected. Some GreenPAKs feature lower resistance than others, making it possible to achieve a given level of efficiency with fewer pins in parallel.

Comparator Design And Programming Output Voltage

The comparator is configured as shown in Fig. 3 by setting the following parameters:

Hysteresis: Enable and set to minimum available value (25 mV). Hysteresis raises the effective reference voltage V_IH, presented in the ACMP settings dialog box, in the Information section.

Low bandwidth: This enables the low pass filter on the feedback input. Use in noisy environments.

IN+ gain: Disable for high input impedance.

IN+ source: Select feedback input pin.

IN- source: Set the initial V_{ref} value as an absolute value (mV), V_{dd} fraction or external Vref as desired. This initial value may be changed via an I^2C command.

The output voltage can be programmed via serial communication by setting the internal reference voltage at the comparator input. Through I^2C the internal reference can be set between 50 mV and 1200 mV in 50-mV steps. Using the feedback resistor divider the regulation can be set to regulate the output voltage to different values.

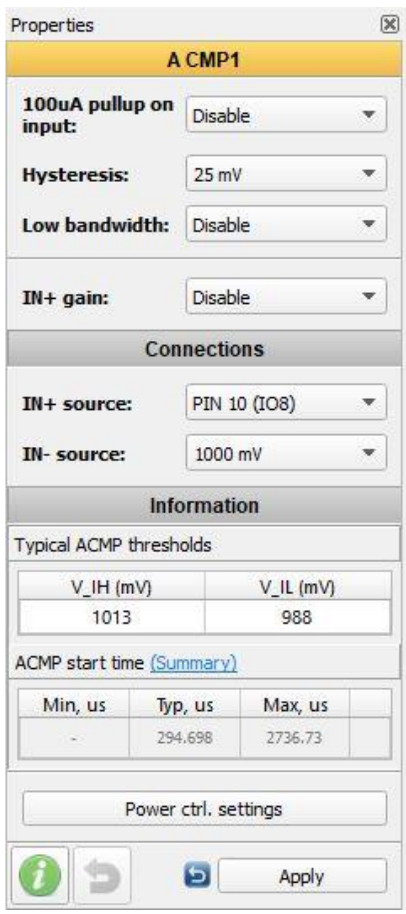


Fig. 3. Comparator settings.

IC Internal Design Schematic

Fig. 4 shows the basic design with only one pin used to drive the Dickson charge pump. The output voltage is not programmable, but the design includes a shutdown feature. Such design simplicity is enabled by the GreenPAK's built-in features. The basic design fits into any GreenPAK that offers an analog comparator block. To increase drive strength, add output pins as available and wire their inputs to the output of the 2-bit LUT0 block.

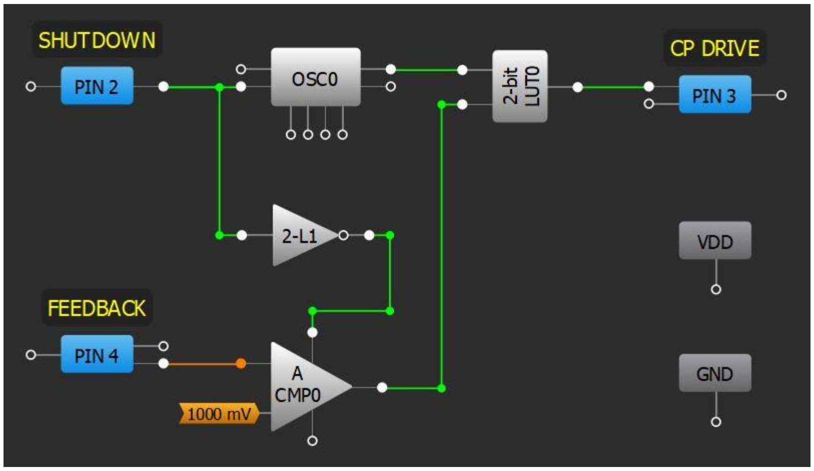


Fig. 4. The basic design of a GreenPAK device in a regulated charge pump.

Fig. 5 shows a design with a programmable output voltage and two shutdown inputs: one direct input, like in the first design, and another via I²C. They are wired through an OR gate so each one can shut down the charge pump independently. If priority logic for shutdown commands is needed, change LUT0 accordingly. This design requires I²C capabilities and it fits into any GreenPAK SLG465xx or SLG468xx. To enable the programmable output the I²C block must be enabled.

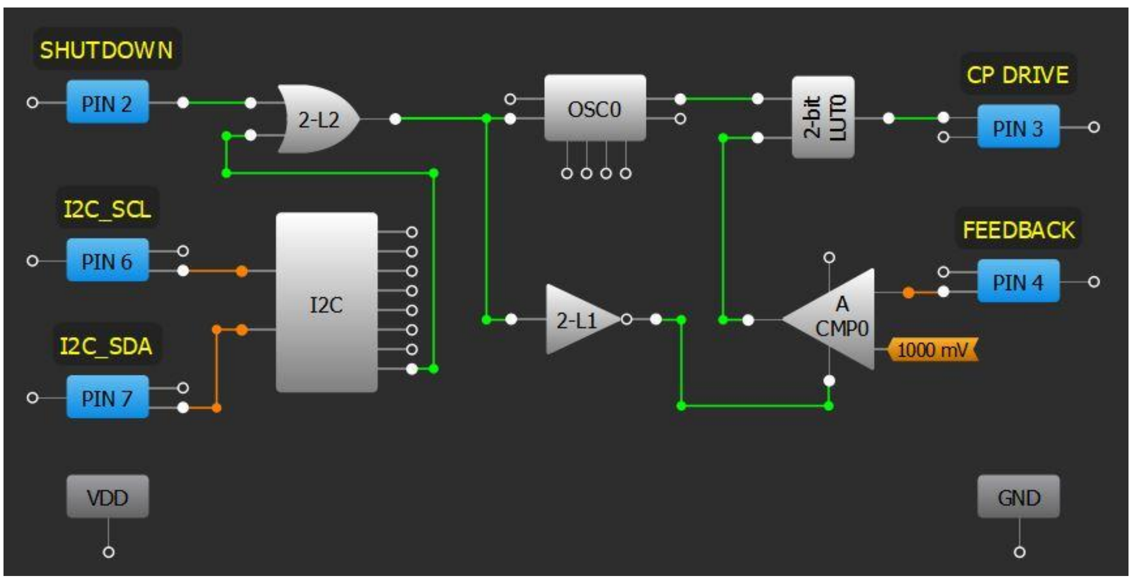


Fig. 5. The design of a GreenPAK device in a regulated charge pump with programmable output.

Powerdown Feature

Design issues regarding a powerdown feature are explained in the application note.[5] Extra design steps are needed to power down the comparator block that performs the regulation: setting the comparator block parameters and applying shutdown signal, as shown in Fig. 4 above.

If a powerdown feature is not needed, the PWR UP input of the comparator (ACMP0) must be wired HI. The POR block is recommended as the HI source in this scenario.

When designing a voltage booster with full shutdown (see the application note again[5]), connect the feedback divider across the load, otherwise it will draw current from the supply rail during powerdown.

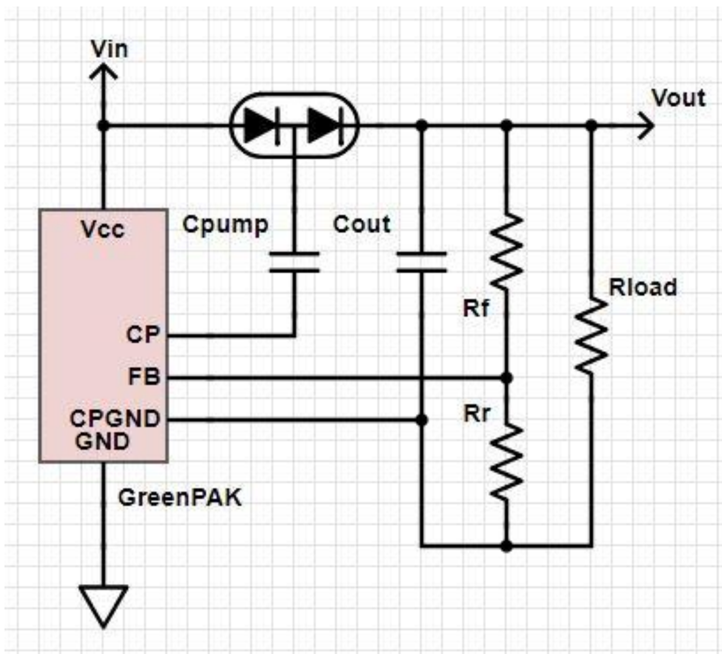


Fig. 6. Regulated charge pump with full shutdown.

Circuit Performance

The following circuit performance specifications in Table 2 apply to charge pumps built with GreenPAK ICs, assuming the following parameters: C_{pump} = C_{out} = 1 μF X7R; D = schottky; T_A = 25°C; f_{osc} = 125 kHz; I_{fb} = 10 uA; R_r = 100 kΩ; R_f = 400 kΩ (5-V V_{out}) or 230 kΩ (3.3-V V_{out}); and V_{ref} = 1000 mV unless otherwise noted.

Table 2. Circuit performance specifications.

Symbol	Parameter	Note	Min	Typ	Max	Unit
V_{in}	Supply voltage		1.71	---	5.5	V
I_{qsc}	Quiescent current	$R_L=\infty$, 125 kHz	---	100	---	µA
I_{shdn}	Shutdown current (note 1)	SLG46533	0.31	0.57	0.89	µA
f_{osc}	Oscillator frequency 25 kHz OSC 2 MHz OSC	selectable (note 2)	0.048 -3.4% -9.4%	$25/2^n$ $2000/2^n$	2000 4.7% 14.4%	kHz
I_{out}	Output current (note 3)		5	10	45	mA
V_{out}	Output voltage accuracy	in regulation	-3	-	+3	%
FB_{imp}	Feedback pin impedance	(note 4)	0.8	100	-	MΩ
P_{eff}	Power conversion efficiency	R_L=5 kΩ	51	63	76	%
V_{th}	Shutdown input threshold High state, device shutdown Low state, device operating	V_{in} = 3.3 V, selectable (note 5)	1.06 0.67	1.81 1.31		V
T_A	Operating temperature		-40	25	85	°C

Notes:

1. I_{shdn} is specified here for the SLG46533, see the relevant datasheet for other Dialog parts; I_{shdn} considers leakage and other parasitics outside GreenPAK negligible; for measured shutdown current which includes feedback current, leakages and other parasitic parameters in a real circuit, not just the GreenPAK CMIC, check Fig. 13b.

2. Selectable to frequencies derived by dividing 25 kHz or 2 MHz: 25 kHz/2 n or 2 MHz/2 n, n=0...9.

3. Column “min”: single pin 2x drive, “typ”: 2 pins in parallel 2x drive, “max”: multiple pins in parallel 2x drive; specified for the SLG46533, see relevant datasheet for other Dialog parts.

4. Depends on comparator configuration, for detailed info refer to Table 1.

5. GreenPAK input levels may be programmed for logic input (min high-level and max low-level shown in column typ) or low-level logic input (min high-level and max low-level shown in column min). The third option is logic input with Schmitt trigger, see GreenPAK datasheet for voltage levels.

Testing And Results

The regulated voltage doubler charge pump external circuit was assembled on a breadboard and connected to a GreenPAK Universal Development Board. The SLG46533 has enough GPIO pins to test multiple pins in parallel. A programmable dc voltage source is connected to the charge pump input. A programmable load is connected to the charge pump output. Two professional high-accuracy multimeters were connected to measure input and output parameters.

For final measurements, the GreenPAK Universal Development Board was removed because it introduces effects in the circuit that impact the measurement results, such as the series resistance of the analog switches. For complete test setup schematics and photos please refer to the application note.[5]

Since the testing includes various configurations, the GreenPAK design for a DUT device is adapted accordingly, so that the charge pump configuration may be changed by digital signals sent from an automated test setup. The GreenPAK design is presented in Fig. 7 and it is intended only for testing purposes. This design includes changes to accommodate test points as well as changes that enable the turning on or off of output pins to reconfigure the circuit.

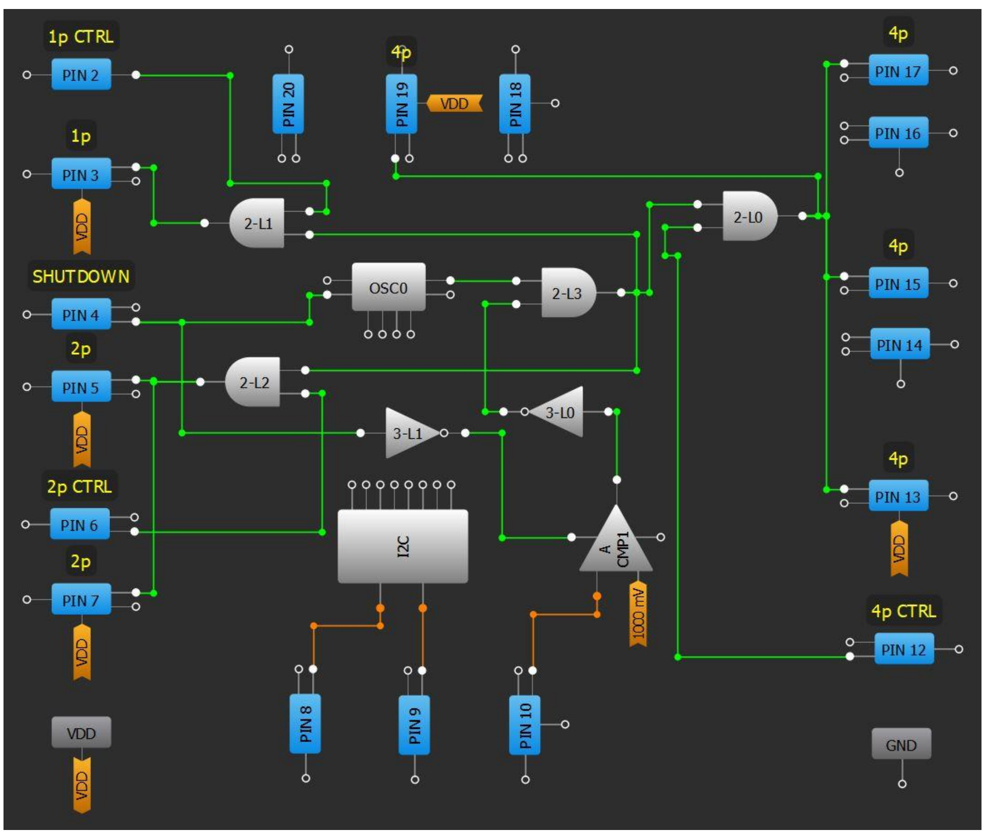


Fig. 7. GreenPAK design for regulated voltage doubler charge pump. This particular design was developed solely for testing.

Graphs

Measurements were obtained for two popular low-cost diode options: standard silicon fast switching diodes 1N4148 and schottky diodes BAT42. Results are presented graphically. In all graphs, the following values and circuit choices are assumed: $C_{pump} = C_{out} = 1\ \mu F$, an X7R ceramic multilayer capacitor; $T_A = 25°C$; and f_{osc} = 125 kHz.

With regard to feedback, $I_{fb} = 10\ \mu A$; $R_r = 100\ k\Omega$; $R_f = 400\ k\Omega$ (5-V V_{out}) or 230 kΩ (3.3-V V_{out}); and V_{ref} = 1000 mV. The circuit is configured as a voltage booster (doubler); full shutdown capability is not implemented; and it is I^2C programmable.

Figs. 8 and 9 show measurements of load regulation at 5-V and 3.3-V output at different values of Vin, with standard and Schottky diodes, plotted on linear and log scales.

Fig. 10 shows measurements of efficiency over the load range at 5-V and 3.3-V output at different values of V_{in}, with standard and Schottky diodes. In all these graphs, f = 125 kHz and drive = 2 pin 2x. (GreenPAK pins can be configured as single drive (1x) and double drive (2x). The 2 pin 2x designation means 2 pins in parallel, each pin configured as a double drive.)

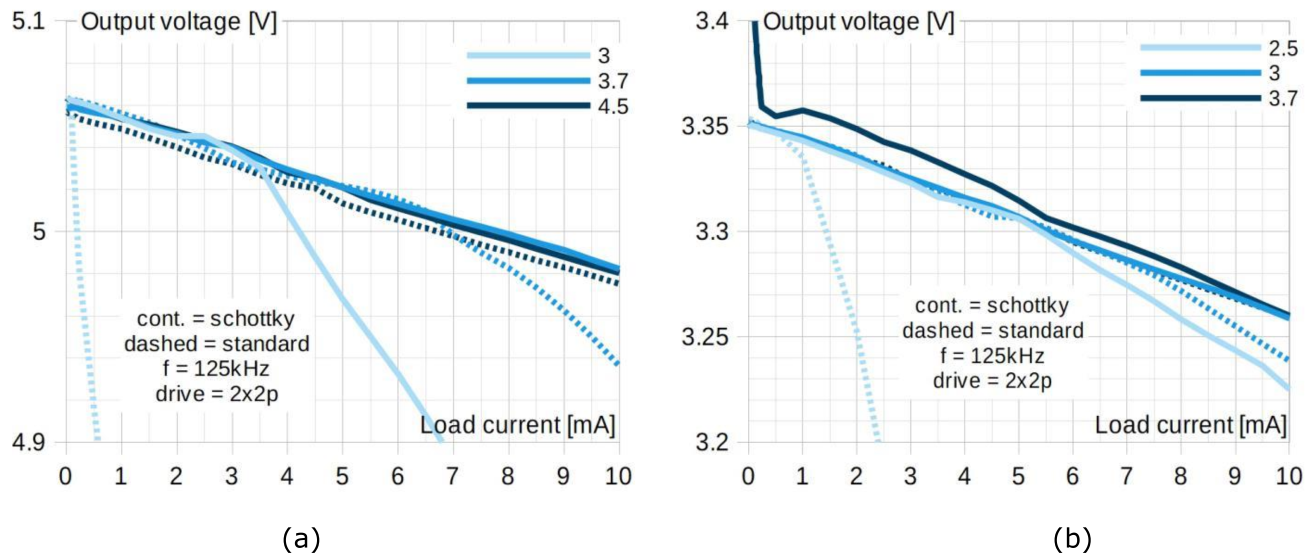
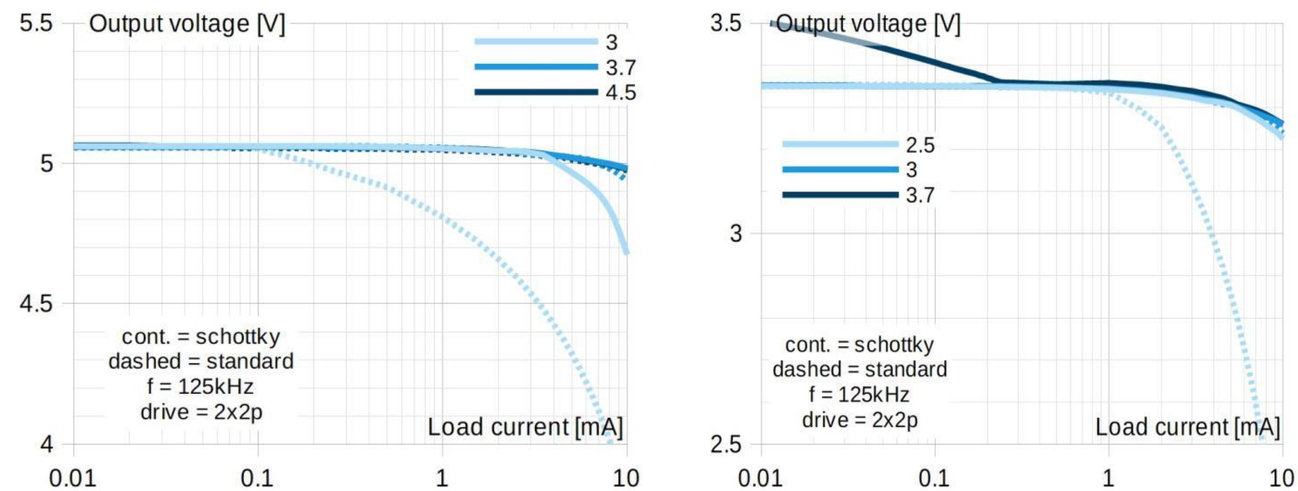
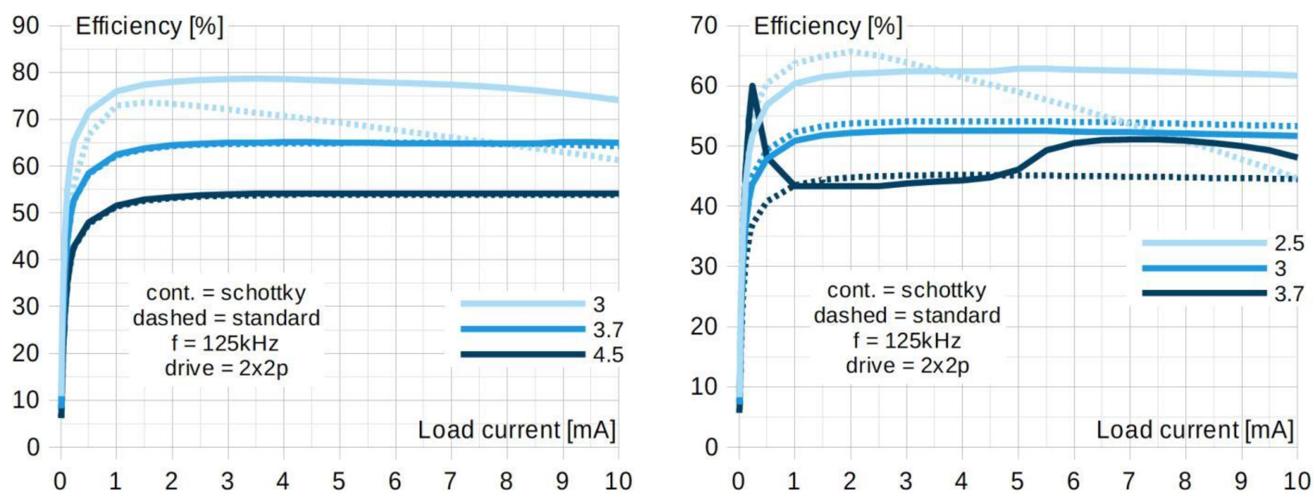


Fig. 8. Load regulation at 5-V output (a) and 3.3-V output (b), linear scale.



(a) (b)

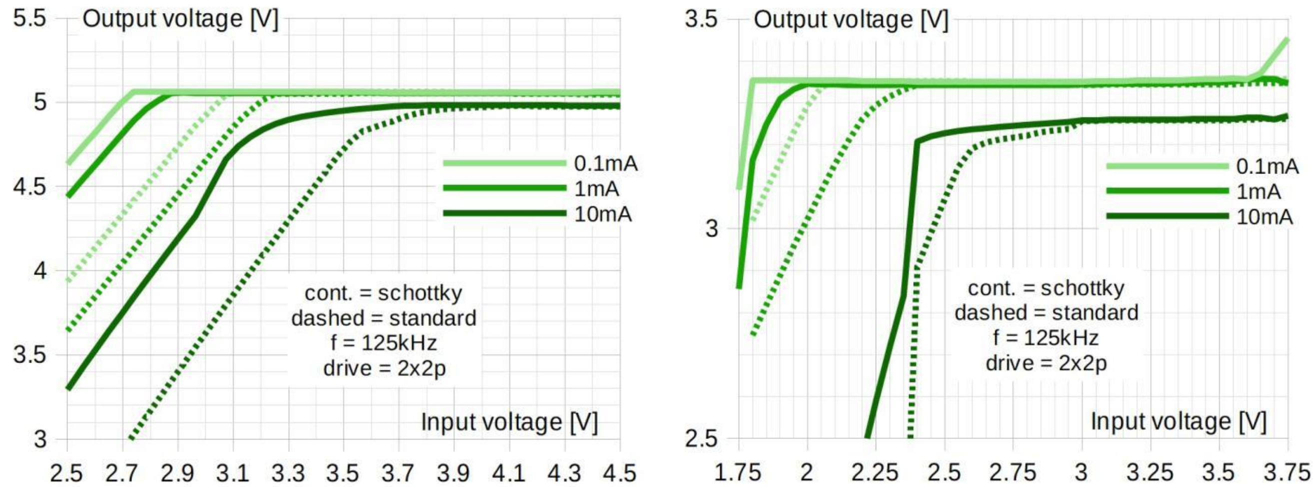
Fig. 9. Load regulation at 5-V output (a) and 3.3-V output (b), log scale.



(a) (b)

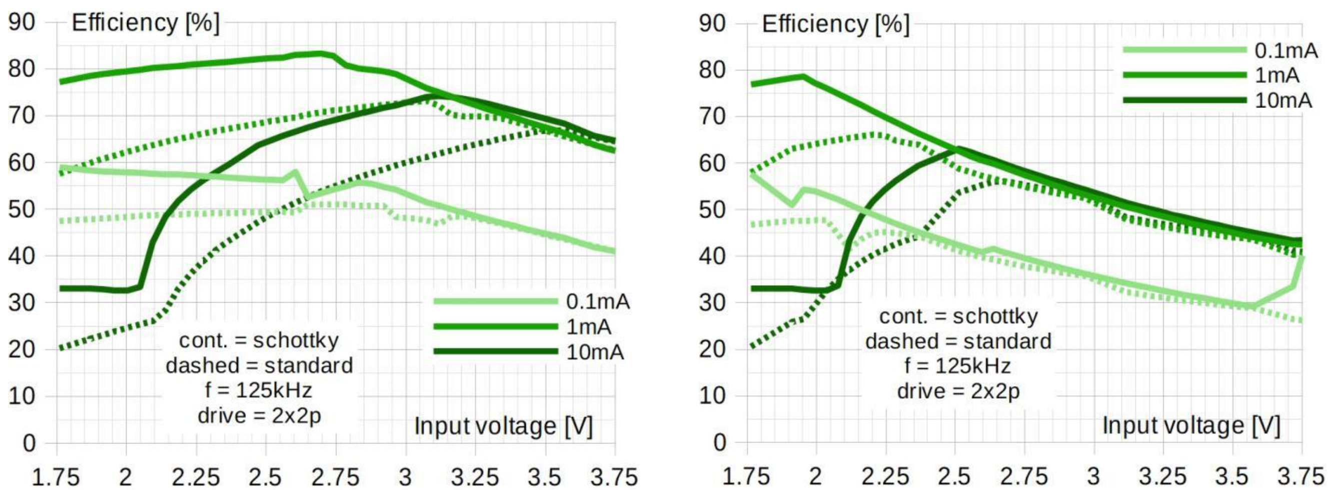
Fig. 10. Efficiency vs load at 5-V (a) and 3.3- V (b) output.

Fig. 11 shows measurements of line regulation at 5-V and 3.3-V output at different values of Iout, with standard and Schottky diodes. Fig. 12 shows measurements of efficiency versus input voltage at 5-V and 3.3-V output at different values of I_{OUT}, with standard and Schottky diodes. Fig. 13 presents plots of quiescent current and shutdown current versus input voltage at 5-V and 3.3-V output, with standard and Schottky diodes. In all these graphs, f = 125 kHz and drive = 2 pin 2x.



(a) (b)

Fig. 11. Line regulation at 5-V (a) and 3.3-V (b) output.



(a) (b)

Fig. 12. Efficiency vs line at 5-V (a) and 3.3-V (b) output.

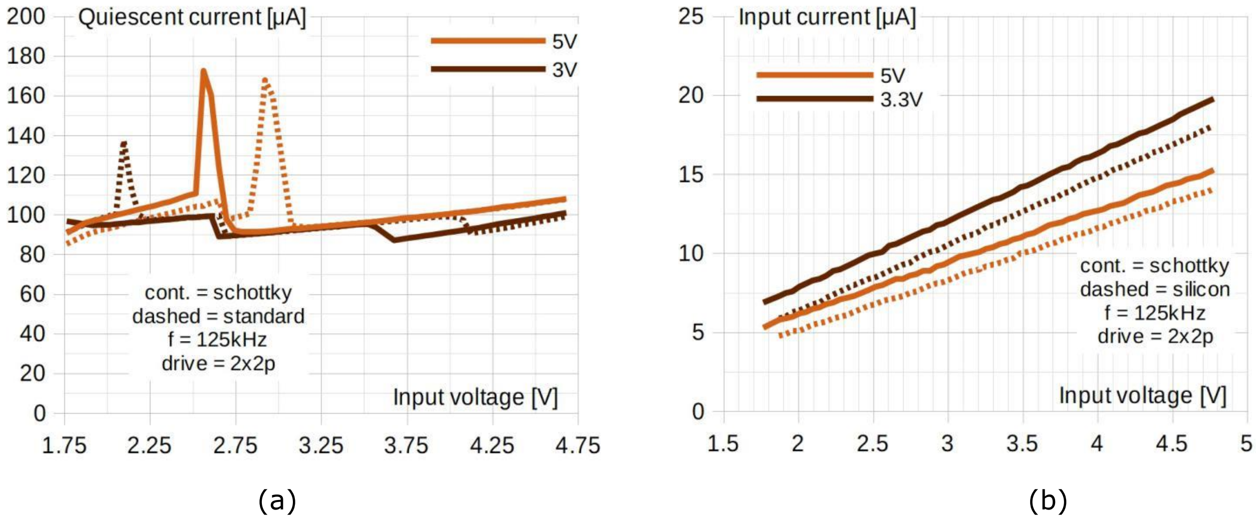


Fig. 13. Quiescent current (a) and shutdown current (b).

Optional Design Modifications And Optimizations

External diodes may be replaced by MOSFETs or analog switches to reduce voltage drop (increase output voltage) and improve efficiency (Fig. 14). In this case the unregulated output voltage is higher than the required regulated voltage, only efficiency will be affected.

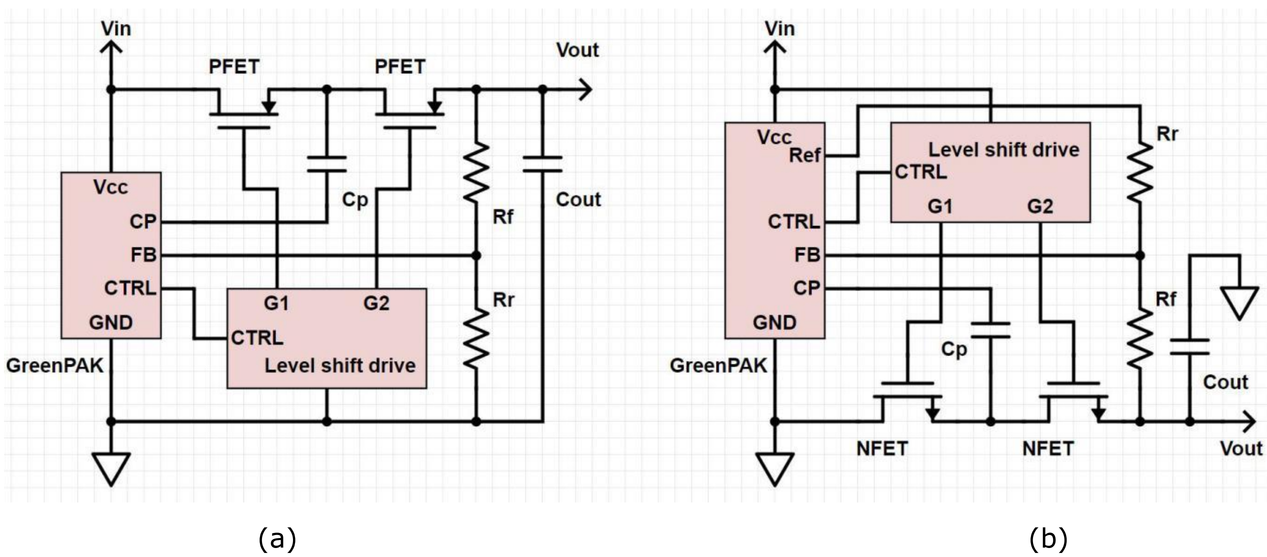


Fig.14. Replacing diodes with MOSFETs in a boost charge pump (a) and an inverting charge pump (b).

Output voltage may be regulated by LDOs or Zener diodes to eliminate output ripple. With a regulated charge pump there is no need to compensate for input voltage and load variations. When using LDOs, output characteristics are similar for regulated as well as for unregulated charge pumps, so a regulated circuit isn't often necessary.

However, using a regulated charge pump with an LDO has the advantages of lower aggregate losses and less heat on the LDO. Higher efficiency is important for battery-powered circuits where the configuration of "regulated charge pump + LDO" may double battery autonomy compared to the "unregulated charge pump + LDO" configuration.

Looking at design modifications and optimizations presented for unregulated charge pumps, it is important to note that with unregulated charge pumps, it is possible to reuse the same driving pins for all charge pumps, if several outputs are required. This is NOT possible for regulated charge pumps, because driving pins are used for regulation and pulse widths for different outputs will not be equal. With regulated charge pumps, you have to use at least one driving pin and one feedback pin for each output. However, it is possible to use the same internal voltage reference for multiple negative outputs, as shown in Fig. 15.

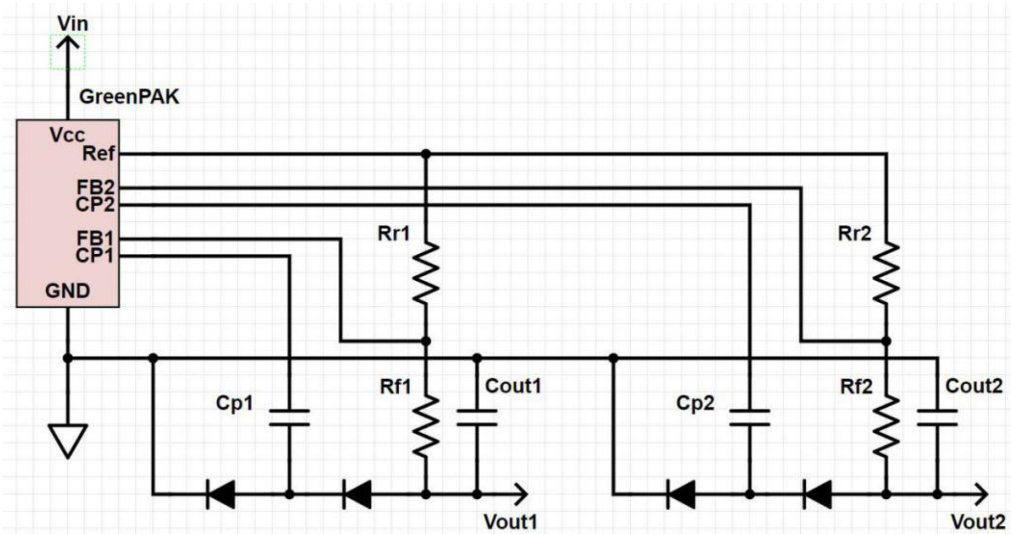


Fig. 15. Reusing the reference pin for multiple outputs.

Key Advantages And Commercial Viability

If you already have a GreenPAK CMIC in your circuit performing other functions, with a couple of unused pins and some free blocks inside the GreenPAK, then it is absolutely commercially viable to implement a GreenPAK regulated charge pump solution because it will take just a couple of additional diodes, capacitors and resistors. The total cost of such a solution at production quantities comes down to cents, five to ten times less than a specialized charge pump IC.

A GreenPAK charge pump solution is also competitive if it is applied solely for a charge pump function. In this case, select a low-cost GreenPAK such as the SLG46110 and you can reach a cost two times less than a specialized charge pump IC solution.

One GreenPAK IC can control multiple regulated charge pump circuits or a combination of regulated and unregulated charge pumps. The cost of each additional charge pump comes down to additional external components, which amounts to a couple of cents per output. With commercial charge pump ICs, each pump comes at full price. With a GreenPAK solution for multiple charge pumps, parameters of each circuit may be programmed independently. Multiple outputs with the same voltage level might be required if separate on/off control is needed or cross regulation effects must be avoided.

With GreenPAKs that feature serial communications, it is possible to control the charge pump circuit via serial communication with a choice of SPI or I²C. On/off control, operating frequency, wake/sleep regime are some parameters to set via serial communications. GreenPAKs with I^2C provide far more configurability from the serial protocol.

In summary, a GreenPAK charge pump solution offers multiple advantages including lower cost, smaller size, multiple outputs with the same IC, programmable operating frequency, serial communications control, lower quiescent current, and surplus logic for additional functions. A GreenPAK solution offers similar or better performance than a standalone charge pump IC and some additional features at a fraction of the price.

For the solution presented in this article to be commercially viable, certain requirements must be within the performance level range that is achievable by a GreenPAK solution. That range is dependent on supply voltage and for exact data please refer to the graphs presented in this article. However, the general requirements are summarized as follows: output current is in the milliamps range (<10 mA) and power conversion efficiency is <90%.

Conclusion

This article presented a high-performance, small-size capacitive charge pump with regulated output voltage that can be built easily using a GreenPAK CMIC and a few low-cost external components. A GreenPAK charge pump operates with input voltages of 1.8 V to 5 V and load currents up to 145 mA. Overall performance peaks at input voltages of 3 V to 5 V and output currents of 1 mA to 5 mA while using schottky diodes.

There are certain "basic charge pump" feature sets where the proposed GreenPAK solution offers lower cost, smaller size or lower quiescent current than specialized ICs. Other applications where a GreenPAK-based charge pump solution is favorable are ones needing specific functions not available in standardized charge pump ICs. The surplus circuitry in GreenPAK, unused in a charge pump circuit, can be utilized in those applications to implement such specific functions. These functions could be directly or closely related to charge pump function but may just as easily be completely independent hardware functions of the target device.

This article does not cover all performance ranges of capacitive charge pumps, but the GreenPAK ecosystem offers the right solution to cover all of them with appropriate design.

For related documents and software, see the GreenPAK landing page.[10] In addition, download the free GreenPAK Designer software[1] to open the .gp files[2] and view the proposed circuit design. Use the GreenPAK development tools[3] to freeze the design into your own customized IC in a matter of minutes. Dialog Semiconductor provides a complete library of application notes[4] featuring design examples as well as explanations of features and blocks within the Dialog IC.

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About The Author

Vladimir Veljkovic has over 25 years of experience in professional grade electronics, primarily embedded, real-time and distributed systems. His professional career evolved from analog & mixed signal (high-power uninterruptible power supply systems) to complex HW/SW electronic systems (large-scale telecom switch). He is versed in mixed HW/SW development process with a focus on system architecture design, automated testing and quality assurance. In recent years he's been involved in the IoT industry and also writes application notes for Dialog Semiconductor.

For more information on designing charge pumps, see the How2Power [Design Guide](), and enter "charge pump" in the Keyword search box.