Integrated Charge Pumps with Low-Dropout Regulator

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**Introduction**

A charge pump is an electronic circuit that uses capacitors as energy storage elements to create either a higher or lower voltage power source. Charge pump circuits are capable of high efficiencies, sometimes as high as 90-95% while being electrically simple circuits. The charge-pump circuit which is used to generate higher voltage than the available supply voltage has wide applications such as the flash memory or EEPROM.

**Circuit Topology**

**Aim**

Our project is to design an integrated charge pump by combining a low-dropout regulator (LDR) with an unregulated 2X charge pump.

To provide low-current 5V power in a 3.3V system, employ a charge-pump chip to double the 3.3V to 6.6V, and then use a regulated LDO chip to reduce 6.6V to 5V. To counteract the effect of high source impedance in the charge pump, provide feedback from the output to the LDO.

**Design Specifications**

**2 X Charge Pump**

When $\phi_1 = 0$, $M_3$ is ON and $C_1$ is charged to $V_{dd}$. When $\phi_1 = 1$, $C_1$ is replaced on top of $V_{dd}$. In many cycles afterwards, $C_2$ will be charged up to $V_o$ to $2V_{dd}$, thus, the charge pump is a voltage doubler.
Low Dropout Regulator with Voltage Buffer
A low dropout regulator (LDR, also known as LDO) capable of operating at a very low input-to-output voltage, usually less than 0.5V at full load, has been widely used as a post regulator of a switching converter.

Voltage-Controlled Oscillator
Voltage-Controlled Oscillator (VCO) is as a clock generator. The frequency of an ideal VCO is independent on the input voltage. However, the clock signal is a triangular signal which is not familiar to be used. Therefore, it is supposed to be modified as a rectangular waveform by Hysteretic Comparator.

Current Mirror
The simple current source uses a diode-connected transistor and a resistor to generate a current that depends on the supply voltage. In many applications, supply-independent source would be used. One of the current source designs is Peaking Current Source.

Simulation Result
After finishing the doubler and low dropout regulator, the doubler is placed in front of the low dropout regulator and this is the integrated charge pump with regulator.
Waveform of 2x charge pump output
Waveform of overall output

The red line is the output of 2X charge pump; it is two times of its input voltage in the steady state. The output of the charge pump provides an input voltage for LDR. The purple one is the output of the LDR. When its input, output of charge pump, is equal to two times of charge pump’s input, LDR will regulate it to 5V. Finally, a fixed 5V output of LDR is obtained.

Conversion Efficiency
The efficiency is equal to the ratio of the actual voltage, simulation output, over the ideal output voltage.

\[ \eta_c = \frac{\text{realized output voltage}}{\text{ideal output voltage}} \]

The conversion efficiency is shown as above. The output voltage range of the charge pump is 5.4V to 7V. The conversion efficiency depends on the load current. It seems that high load current affects the efficiency much heavily. The overall efficiency is larger than 92%. This design is better the previous one about 2% evenly. As the result, VCO should be chosen as the clock generator of the integrated charge pump with LDR.

Power Efficiency
The efficiency is equal to the ratio of the power supply for load divided by the power consumption of the source.

\[ \eta_p = \frac{V_o I_o}{V_i (I_o + I_q)} \times 100\% \]

The overall power efficiency is limited by the LDR. The higher voltage supplied to the LDR is, the lower power efficiency the LDR will be. Even if the quiescent current is small, the ratio of \( E_{\text{out}} \) over \( E_{\text{in, LDR}} \) is also limited by the unregulated input voltage. Therefore, when the \( V_i \) increases, the power efficiency will be reduced.