An EMI-Reduction design with Charge Pump Circuit and Hybrid Modulation Technology for a Motor Driver Applications in 0.18um BiCMOS process

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An EMI-reduction charge pump circuit with hybrid modulation is proposed for the motor driver circuits. Periodic modulation technique changes the range of spread spectrum as coarse modulation. Random modulation technique, as fine-tuning, changes its edge delay to slow the speed of switch-edge. Simultaneously, the proposed buffer circuit can limit the charge and discharge current of the charge pump and reduces the variation of the current peak. Compared with the circuit without modulation, EMI is reduced by up to 28dB. The proposed design fabricated in a 0.18um BiCMOS process occupies an area of 0.173mm^2, and its power consumption is 5.677mW.

Introduction: Electromagnetic interference (EMI) is attracting more and more attention in the explosive growth of portable and consumer electronic devices. Besides the impact of EMI on the functionality of electrical devices, it may also threaten human health. EMI is especially vital in high voltage circuits [1], e.g, motor driver applications.

The charge pump circuit is essential in the high voltage DC motor driver circuit with double n-channel power MOSFET. Usually, the load capacitance is introduced as a built-in cap for cost reduction. A higher switch frequency will be introduced to maintain the circuit's driving capability. In this high-voltage/high-frequency case, voltage (dV/dt) or current (dI/dt) with a high variation slope will appear during switching, resulting in a more severe EMI problem[2].

The spread spectrum clock generation circuit (SSCG) is one effective way to reduce EMI. It can spread energy to a broader frequency band to reduce the peak and harmonic radiation emissions. The direct modulation voltage-controlled oscillator (VCO) can be easily implemented in SSCG and can obtain better electromagnetic interference reduction performance.Modulation methods include periodic signal modulation[3][4], random signal modulation[5], and chaotic signal modulation[6]. Large-area capacitors and inductors are needed with chaotic signal modulation, which may not be suitable for motor driver circuits and processes. Besides, the waveform of periodic modulation includes triangular wave[3], sine wave, and Hershey-Kiss wave[4]. The spectrum modulated by the Hershey Kiss waveform is an energy distribution with equal amplitude, and the spread spectrum is effective. Nevertheless, many registers are needed. The complex control method consumes a large circuit area and chip cost. The triangular wave has high controllability and a good spread spectrum effect. It is convenient to implement. Although random modulation is more effective than periodic modulation and has little impact on audio performance, a real random signal is difficult to obtain. Therefore, pseudo-random signals are usually used.

In this paper, we propose an EMI-reduction charge pump circuit with hybrid modulation for the motor driver circuits. Simultaneously, the current source driven by an external control voltage is replaced by a small current source with constant conduction in the buffer circuit. It limits the charge and discharge current of the charge pump and reduces the variation of the current peak. Compared with the method of constant reference current[2] or adjustable reference current[7], it saves area and power consumption.

Theoretical analysis and MATLAB simulation verification: The traditional periodically modulated signal is:

$$S_{FM}(t) = A\cos(\omega_c t + \frac{\Delta\omega_{max}}{\omega_m}\sin\omega_m t) = A\cos(\omega_c t + \beta_F \sin\omega_m t) \quad (1)$$

where modulation coefficient is $\beta_F = \frac{\Delta\omega_{max}}{\omega_m} = \frac{\Delta f_{max}}{f_m}$. By the Fourier transform, the spectrum of traditional periodic signal modulation is :

$$S_{FM}(\omega) = \pi \cdot A\sum_{n=\infty}^{\infty} Jn(\beta_F)[\delta(\omega - \omega_c - n\omega_m) + \delta(\omega + \omega_c + n\omega_m)] \quad (2)$$

It can be seen from the above formula that the frequency spacing of the carrier signal can become $\pm nfm$, and the amplitude of Jn (β_F) decreases with the increase of β_F. In the proposed modulation mode, assuming that the frequency of periodic modulation is fm1 and the frequency of random modulation is fm2, the modulated signal can be expressed as :

$$S_{FM}(t) = A\cos(\omega_c t + \frac{\cos\omega_{m2}t}{\omega_{m1}}\sin\omega_{m1}t) \quad (3)$$

Eq.(3) with trigonometric function:

$$S_{FM}(t) = A\cos\omega_c t \cdot \cos(\frac{1}{\omega_{m1}}\cos\omega_{m2}t \cdot \sin\omega_{m1}t) - A\sin\omega_c t \cdot \sin(\frac{1}{\omega_{m1}}\cos\omega_{m2}t \cdot \sin\omega_{m1}t) \quad (4)$$

where

$$\cos\omega_{m2}t \cdot \sin\omega_{m1}t = \frac{1}{2}[\sin(\omega_{m2} + \omega_{m1})t - \sin(\omega_{m2} - \omega_{m1})t] \quad (5)$$

where $2\pi(fm2 + fm1) = a$, $2\pi(fm2 - fm1) = b$, according to Eq.(5), and obtain

$$S_{FM}(t) = A\cos\omega_c t\cos(\frac{1}{2\omega_{m1}}(\sin at - \sin bt)) - A\sin\omega_c t\sin(\frac{1}{2\omega_{m1}}(\sin at - \sin bt)) \quad (6)$$

where $\frac{1}{\omega_{m1}} = k$, according to the expansion theorem of trigonometric functions:

$$cos(k(\sin at - \sin bt)) = cos(k\sin at) \cdot cos(k\sin bt) + sin(k\sin at) \cdot sin(k\sin bt) \quad (7)$$

$$sin(k(\sin at - \sin bt)) = sin(k\sin at) \cdot cos(k\sin bt) - cos(k\sin at) \cdot sin(k\sin bt) \quad (8)$$

Change Eq.(7) and Eq.(8) into a triangular series with Bessel functions as coefficients:

$$cos(k\sin at) = J_0(k) + 2\sum_{n=1}^{\infty} J_{2n}(k) \cdot \cos 2nat \quad (9)$$

$$cos(k\sin bt) = J_0(k) + 2\sum_{n=1}^{\infty} J_{2n}(k) \cdot \cos 2nbt \quad (10)$$

$$sin(k\sin at) = 2\sum_{n=1}^{\infty} J_{2n-1}(k) \cdot \cos(2n-1)at \quad (11)$$

$$sin(k\sin bt) = 2\sum_{n=1}^{\infty} J_{2n-1}(k) \cdot \cos(2n-1)bt \quad (12)$$

According to Eq.(7)-Eq.(12), rewriting Eq.(6) using the Bessel function can be:

$$S_{FM}(t) = A\sum_{n=-\infty}^{+\infty} Jn(k)\cos(\omega_c t + nat) + A\sum_{n=-\infty}^{+\infty} Jn(k)\cos(\omega_c t - nbt) - Acos\omega_c t \quad (13)$$

By the Fourier transform, the spectrum of the modulated signal is :

$$S_{FM}(\omega) = \pi A \sum_{n=-\infty}^{+\infty} Jn(k)(\delta(\omega - \omega_c - na) + \delta(\omega + \omega_c + na) \tag{14}$$

$$+ \delta(\omega - \omega_c + nb) + \delta(\omega + \omega_c - nb))$$
$$- \pi A \delta(\omega - \omega_c) - \pi A \delta(\omega + \omega_c)$$

It can be known from Eq.(14) that the modulation frequency spacing is $\pm n(fm2 + fm1)$ and $\pm n(fm2 - fm1)$. If fm2 ≪ fm1, the frequency spacing can be the same as $nfm1$. Therefore, compared with the traditional periodic modulation contour (fwm), the modulation frequency spacing of the proposed method is smaller, and its fundamental frequency amplitude is reduced. In summary, the power spectrum of the proposed modulation method has more various frequencies and reduces the frequency interval and the amplitude of the fundamental frequency. As a result, the harmonic peak can be reduced even more.

The power spectrum of square wave signal with a frequency of 2K is shown in Fig. 1(a), and the effect of periodic modulation and random modulation is compared by MATLAB simulation waveform. The results are shown in Fig. 1(b), Fig. 1(c). It can be seen that under the same conditions, the effect of random modulation is better than that of periodic modulation. The intuitive comparison of the power spectrum in Fig. 1(d) shows that the effect of the hybrid modulation method to reduce EMI is more remarkable.

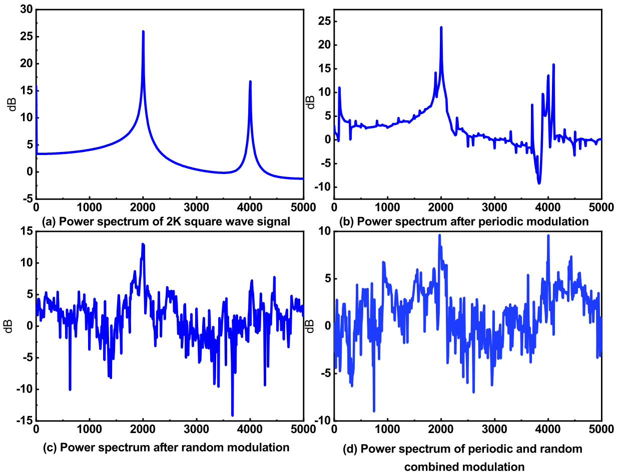

Fig 1 *Schematic diagram of Matlab simulation.*

circuit design: The overall block diagram of the charge pump proposed in this paper is shown in Fig. 2. The coarse adjustment procedure is carried out first. Iosc is the current signal with triangular veins, and the output frequency is adjusted by changing the charge and discharge current of capacitor C. The output signal is fed back to control switches S1-S4, generating a continuously changing oscillation signal. Random signals are generated by Linear Feedback Shift Register (LFSR), which is fine-tuned at the output terminal. Its load size is randomly selected to change its delay to slow the switching edge. As a result, a significant current spike induced by the switch's instantaneous opening can be reduced. Periodic and random modulation share a comparator circuit to realize hybrid modulation and save area.

The schematic diagram of the complete frequency change and the hybrid modulation is shown in Fig. 3. Since the generated signal oscillates in the low-voltage domain and cannot drive the charge pump in the high-voltage domain, a level shift circuit is required to boost the oscillation signal to the high-voltage domain. The raised oscillation signal passes through a low di/dt buffer circuit to control switches S5-S8. The buffer circuit replaces a current source driven by an external control voltage with a small current source with constant conduction. Limiting the charge and discharge current of the charge pump can reduce the variation of peak current. It can also reduce the number of devices used and

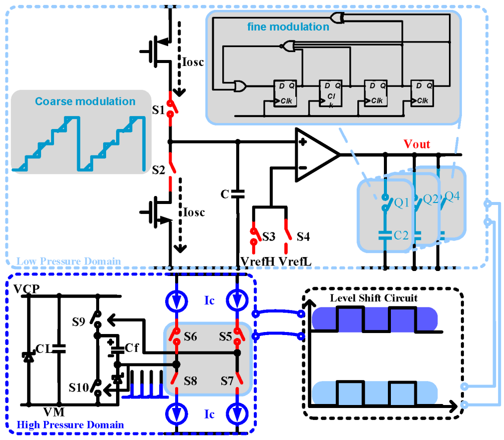

Fig 2 *The proposed circuit block diagram.*

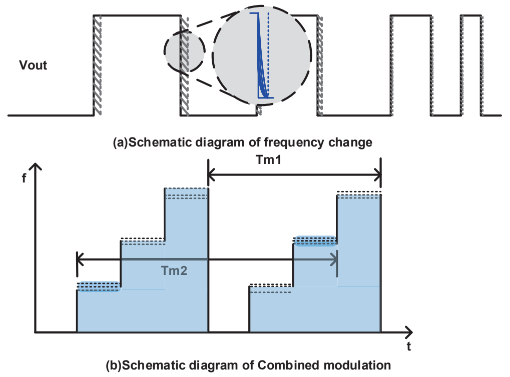

Fig 3 *Schematic diagram of hybrid modulation.*

power consumption and ensure that it has no affection on the reduction of switching speed, which can further suppress EMI. Finally, the output signal from the buffer circuit drives the first-stage charge pump circuit, and the potential is raised to $VM + \Delta V$ to obtain the final output signal VCP.

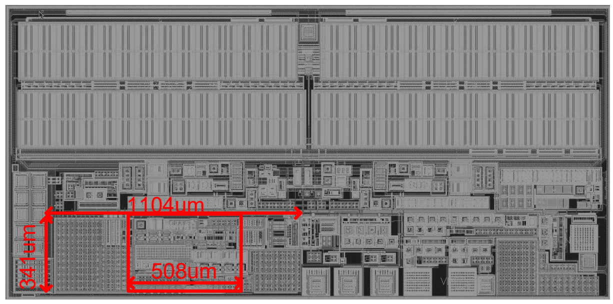

Fig 4 *layout design.*

Results: The proposed charge pump circuit is fabricated in a 0.18um BiCMOS process. As shown in Fig. 4, the charge pump core area is $1100um \times 341um$, of which the area of SSCG is $508um \times 341um$, and the power consumption is 5.677mW. Figure 5 shows the spectrum at 27°C without modulation and with modulation. EMI is decreased by 19dB at 10MHz, whereas EMI is reduced by 28dB at 30MHz. Figure 6 shows the performance of EMI reduction at different process corners and temperatures. It can be observed that EMI is also reduced by 17dB in the worst case. Table 1 compares the performance of the proposed circuit and other SSCGs, demonstrating that the proposed high voltage charge pump circuit can achieve low EMI characteristics. At the same time, it has a small area and low power consumption, which is suitable for motor driver applications.

Table 1. Performance comparison.

Reference	[2]	[4]	[5]	[6]	[8]	[9]	this work
Target application	DC/DC Converters	General purpose SSCG	D amplifier	DC/DC Converters	LCD driver	SOC	Motor driver
Modulation method	Clock Slope Control Technique	ΔΣ +Hershey Kiss	PseudoRand	Chaotic /PseudoRand	DDL+ PseudoRand	All-Digital+ highly discontinuous modulation profile	Triangular +PseudoRand +output buffer
EMI Reduction(dB)	10.5	19.14-24.8	15	17.6	3	15.8	28(@30MHz) 19(@10MHz)
RBW(KHz)	120	100	120	9	120	120	120
Area(mm^2)	2.32	0.076	1	-	14.935	0.102	0.173
Power disipation	3.2mW	23.72mW	0.05W-0.7W	-	8.093mA@10V 54MHz	48.5 (dual output@1.45 GHz) 34.0 (single out@1.45 GHz)	5.677mW
Technology	180nm	130nm	180nm	180nm	-	65nm	180nmBiCMOS

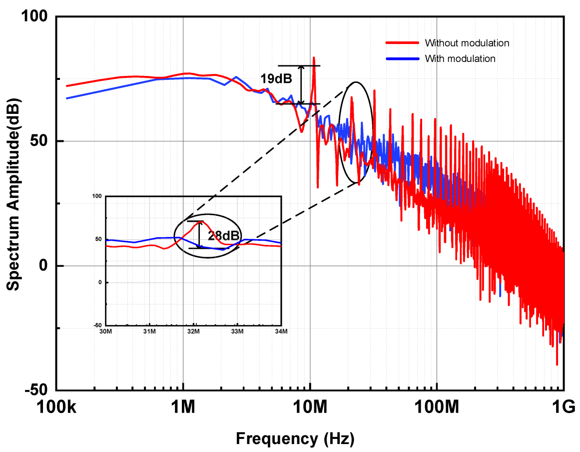

Fig 5 *Spread Spectrum Simulation Results.*

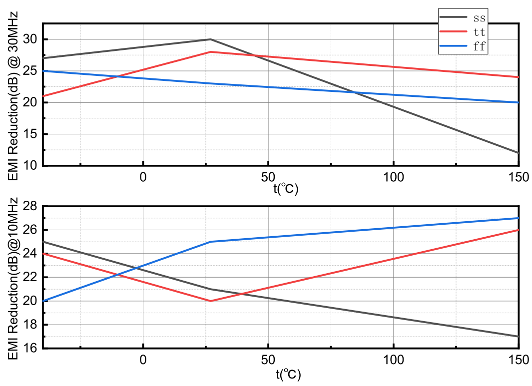

Fig 6 *Simulation of different process corners.*

Conclusion: This paper proposes a new EMI-reduction charge pump circuit with hybrid modulation for the motor driver circuits. The periodic modulation technique is used for coarse tuning, and the random modulation technique is used for fine-tuning. Simultaneously, EMI can be further reduced by the buffer circuit with a small current source. The proposed circuit is fabricated by a 180nm BCD process and occupies an area of 0.375mm^2, of which the area of SSCG is 0.173mm^2. Compared with the circuit without modulation, EMI is reduced by up to 28dB at 30MHz. And the power consumption is 5.677mW. The proposed circuit can be applied as a power supply module to supply power to power transistors in the motor driver circuits.

References

1. Ryu, H., et al.: A spread spectrum clock generator using a programmable linear frequency modulator for multipurpose electronic devices. IEEE T. ELECTROMAGN. C. 57(6), 1447–1456 (2015). doi:10.1109/TEMC.2015.2442618
2. Kennedy, S., Yuce, M.R., Redouté, J.M.: A low-emi fully integrated switched-capacitor dc/dc converter. IEEE T. ELECTROMAGN. C. 60(1), 225–233 (2018). doi:10.1109/TEMC.2017.2702114
3. Guo, H.Y., et al.: An advanced spread-spectrum clock generator with triangular modulation for emi suppressing. In: 2012 International Conference on Wavelet Active Media Technology and Information Processing (ICWAMTIP), , pp. 342–345. (2012)
4. Hwang, S., et al.: A 3.5 ghz spread-spectrum clock generator with a memoryless newton-raphson modulation profile. IEEE J. Solid-State. Circuits. 47(5), 1199–1208 (2012). doi:10.1109/JSSC.2012.2183970
5. Jin, C., Tan, M.T., See, K.Y.: Filterless class-d amplifier with pseudorandomized carrier frequency modulation for emi reduction. IEEE T. ELECTROMAGN. C. 55(1), 74–80 (2013). doi:10.1109/TEMC.2012.2212907
6. Pareschi, F., et al.: Short-term optimized spread spectrum clock generator for emi reduction in switching dc/dc converters. IEEE T. CIRCUITS-I. 61(10), 3044–3053 (2014). doi:10.1109/TCSI.2014.2327273
7. Nuernbergk, D.M., et al.: Design of an emc-improved regulated charge pump in 180-nm cmos technology. In: ANALOG 2018; 16th GMM/ITG-Symposium, , pp. 1–4. (2018)
8. Ko, J., et al.: Spread spectrum clock generator for reducing electro-magnetic interference (emi) noise in lcd driver ic. In: 2007 50th Midwest Symposium on Circuits and Systems, , pp. 1106–1109. (2007)
9. De Caro, D., et al.: A 1.45 ghz all-digital spread spectrum clock generator in 65nm cmos for synchronization-free soc applications. IEEE T. CIRCUITS-I. 67(11), 3839–3852 (2020). doi:10.1109/TCSI.2020.3008481