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High-Order Temperature Compensation for Bandgap Reference Circuits

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Abstract. Bandgap reference is a power source that can be used to enable a constant power output that is independent of temperature. It is important in both the analog and the digital circuit that need high precision reference voltages. In this paper, a brief introduction is made on the development trends of bandgap reference circuits. It begins with the high-order compensation methods of bandgap references and discusses the merits, demerits, and new features of available techniques, including the compensation of polynomials, compensatory curvature and segmented compensation, low power and low limit lifestyles. Lastly, the analysis above, it outlines the development trend of high-order temperature compensation technology. It shows that the high-order temperature compensation has become an essential and important part of the contemporary reference circuits.

Keywords: Bandgap reference, High-Order Temperature Compensation, Curvature Compensation

1. Introduction

Design and production of complex digital circuits have also become easy and convenient with the development of artificial intelligence. This should not, however, mean that digital circuits will be substituting the analog circuits. Quite the contrary, the demand of a high-performance analog circuit to accommodate demanding conditions of operation is growing. To control the bandgap reference circuit is the most important element in analog circuits in IC design to offer a voltage reference of low temperature coefficient and high ratio of power supply rejection to the reference. It provides consistent and accurate reference current or voltage to circuit components, including operational amplifiers, computerized digital-to-analog converters (DACs), computerized analog-to-digital converters (ADCs), low dropout linear regulators, and other sensors. As the integrated circuits have advanced, there is high demand in high precision and low power devices that can work under extreme environmental conditions. Circuits based on traditional bandgap reference (BGR) no longer fulfill temperature coefficient as well as power supply noise immunity requirements. Therefore, temperature compensation technology of high order is being incorporated into bandgap reference circuits more and more frequently.

The high-order temperature compensation circuit attempts to solve the problem in the traditional BGR circuits in which, as temperature changes relative to the reference temperature, nonlinear terms

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lead the temperature curve to deviate from the horizontal line, creating an increasing degree of temperature drift. The base first-order temperature-compensated bandgap reference circuits of the traditional type typically provide temperature compensation by simply summing complementary positive temperature coefficient (ΔVbe) and negative temperature coefficient (Vbe) characteristics linearly. Nonlinear temperature dependence in device physics, however, makes this method a poor way to effectively suppress higher-order curvature errors, and this increasingly limits its suitability to the needs of high-end applications. This has made a research on higher-order methods of compensation mainstream.

The present paper very lightly describes two large trends in the evolutionary history of BGR circuits. In the traditional bandgap reference domains and dealing with the problem of poor output accuracy, it adds high-order temperature compensation. The discussion will include the techniques of the polynomial temperature compensation, curvature compensation and segmented compensation, the low-power and the low-noise design solutions.

2. BGR circuit development trends

As process nodes are scaled to deep sub-nanofinished, Moore's Law is becoming more pronounced: chip performance doubles and feature sizes are becoming smaller and smaller. The conventional bandgap reference circuit suggested by Widlar [1] has low accuracy of output and large temperature drift. As a result, BGR circuits have to exist with reduced supply voltages and the strong impact of short-channel modulation in this regime, mainly by exploring the two aspects mentioned below. The voltage going to the processes in low-voltage operation gradually reduces with the progress of the processes to submicron and deep submicron nodes. State-of-the-art processes frequently need voltages that are smaller than 1V or even 0.8V and can no longer be supplied by the conventional BGR circuit power supplies. By using a temperature-compensated current sensing circuit to reduce resistance, the Fudan University team was able to achieve the goal of 0.95 V operating the resistive shunt-type low-voltage bandgap references [2]. Hspice simulation tests of SMIC process simulations of 0.18μm process indicate that the circuit can reliably be run at a minimum of 0.8 V and requires 40μW of power. Secondly, it is important to optimize the high power supply rejection ratio (PSRR). Noise of power supplies at high frequencies (above 100kHz) grows progressively as the feature sizes reduce and is extremely high at frequencies in the microwave frequency range (cumulatively in the 3kHz to 300kHz range). This noise has a detrimental effect on the precision of output reference voltages, especially in a mixed-signal analog chip. Stabilization of circuit systems is thus very crucial to the enhancement of PSRR capability. Recent studies have taken PSRR beyond low-frequency suppression up to high-frequency suppression. Some of the techniques available to improve PSRR are: common-mode feedback, cascode structures, passive RC networks, common-source common-gate (CSMC) structure [3], and pre-calibration [4]. Feng Xiuping et al. [5] came up with an adaptive folded common-source common-gate feedback error amplifier. They used asymmetric adaptive common-source common-gate transistors in order to maximize gain, and, with a CSMC 0.18μm process, had managed PSRR at -72.4 dB@10 kHz.

3. Up-to-date condition of the advanced temperature compensation technology

The temperature stability and immunity to noise of reference voltages in consumer electronics, power management and high-precision measurements and data acquisition systems are highly important. Conventional BGR circuits find this difficult, resulting in the development of high order temperature-compensated BGR circuits. These technologies have become very popular and

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widespread in research. In order to have steady voltage production in extreme temperatures, Zhang Jie et al. [6] verify the importance of having high-order compensation techniques in attaining excellent values of temperature coefficients in the process conditions, hence the wide applications to system-level cases that highly demand voltage regulation and noise characteristics are attained.

3.1. Technology of polar temperature compensation polan

Polynomial temperature compensation technology seeks to add high-order temperature-dependent additional terms to bandgap reference circuits in order to better compensate those nonlinear changes in device parameters with respect to temperature, reduce temperature coefficients and curvature errors. According to Zhang Xueyong and Liang Zien [7], as the size of devices gets smaller and the processes become increasingly complicated, first-order linear compensation is no longer able to achieve high precision under a broad temperature set of conditions. As a consequence, there is a large amount of recent interest in polynomial compensation as an effective means of curve direct fitting of temperature response curves at the circuit level [7]. The technology normally produces compensation elements that have a quadratic or higher order dependence on temperature, with the creation of suitable current sources, resistor networks, or capitalizing on device nonlinearities. It allows making finer-grained corrections to the nonlinear curvature of the base-emitter voltage. Polaroid Compensation Polaroid compensation greatly minimizes the total drift in temperature over a wider temperature span compared to classical techniques, which use only a single temperature coefficient. It also, however, comes with greater complexity in the circuit, increased sensitivity in the devices, and increased dependence on processes. Designs that are applied in the real world demand a compromise of the compensation order, implementation method and circuit stability. Circuit simulation and experimental verification are used to optimize the compensation coefficients in order to reach a desired power consumption, size, and accuracy tradeoff [7].

3.2. Segmented compensation methods and curvature compensation

Compensating curvature usually consists of the introduction of additional higher-order terms, with regard to temperature, in the voltage or current components of the bandgap core. This forms total output curvature that contradicts the nonlinearity in the temperature dependence of the device, which allows it to be better fitted and compensated. Such implementation methods involve taking advantage of the nonlinear current-voltage behaviour of the device, and assistance of temperature-sensitive resistive network, or exploiting the nonlinear behaviour of carefullybiased active devices to produce the desired higher-order temperature behaviour. Segmented pay is a method used to obtain a very accurate temperature pay by subdividing the operating temperature range into several sub-zones. It adds voltage or current components to various temperature coefficients within a given sub-zone with specific weights given to them. The resulting process gives a reference voltage or current, whose temperature coefficient is close to zero, in each sub-zone. Segmentation strategy may either be based on automatic circuit switching between different operating points, or based on digital control and look up table use of different values of compensation in different temperature ranges.

Both process operations have their own strengths and weaknesses in use. Curvature compensation has the benefit that it does not switch to transients but does constant correction in the analog domain and therefore provides stability in the situation of process drift. Its complexity of design has been due, however, to the necessity of properly describing the higher-order temperature behaviour of the device and applying equivalent compensating terms in the circuit, which causes a correspondingly higher complexity of the circuit and a more effort-intensive debuging effort. Segmented

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compensation, in contrast, has been shown to predict local fitted performance better over a broad range of temperatures, and is therefore especially well suited to extreme temperature conditions. Nevertheless, it generally needs temperature detection circuitry, temperature zone control logic, or digital control units, which add to the power consumption and space cost. Jia et al. [8] liked in 2024 suggested computing a compensation term based on voltage difference (Vbe) between the emitter and base of two bipolar junction transistors (BJTs), and added an absolute temperature proportional (PTAT) and an absolute temperature zero (ZTAT) current to the emitter-base of a single BJT. It is observed in simulations that were run in a 0.18μm bipolar-CMOS-DMOS process that a typical TC of 2.25×10^{-6}/°C exists between -40 °C to 125 °C.

Recent studies have gone a step further to combine and optimise the segmented compensation and curvature compensation and show encouraging results of enhanced performance within the broad temperature ranges. The method has the disadvantage that it requires tremendous accuracy in modelling of devices in matching them with temperature-sensitive components and the design must take into account process variations and long-time reliability [9]. At the same time, with the increased stability of device parameters in more complex processes and more accurate methods of modeling curves, it has become possible to implement the technique of the simulated curvature correction with higher accuracy and efficiency. Also, digitally assisted segmented compensation, via the use of low-power temperature sense and fine-tuning is capable of substantially improving performance over wide temperature ranges without becoming power-hungry in general. Continuous curvature compensation vs discrete segmented compensation Engineers often consider continuous curvature compensation vs discrete segmented compensation applicable in different application conditions and design options, or use mixed approaches to trade-off between accuracy, power consumption and implementation cost. These high-order forms of compensation have been found to provide a major benefit of minimizing temperature-related curvature errors in real circuits and improving the stability and reliability of bandgap references over large temperature variations [10].

3.3. Low power, low noise design

Low power consumption and low noise are frequently at odds in high-end temperature-compensated BGR designs, and need to be balanced together through structural and circuit design. Typical methods are biasing at subthreshold or near threshold to minimize constant power consumption, coupled with dynamic current gating to shut off idle modules without affecting temperature compensation accuracy; using current mirrors and differential design to deliver the best possible noise distribution, according to which the effects of 1/f noise on the reference point are minimized. On-chip power management separates the analog reference and the digital power supplies and eliminates the switching noise coupling. In layout, sensitive components should be placed strategically close to reference resists and also interconnect lengths in sensitive loops should be reduced in order to minimize noise and drift induced by thermal gradients and parasitic resistances. In order to ensure high accuracy at very low power, more and more designs include: maintaining the reference at low power in low-frequency/idle conditions, and periodic wake-up to allow rapid calibration to reduce long-term drift. A comparison between a few of the strategies is made against power consumption and noise lowering in Table 1.

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Table 1. Low-power and low-noise comparison

Strategy Categories	Power consumption impact	Noise Reduction	Complexity of Implementation	Applicable Scenarios
Subthreshold voltage offset	Extremely low	General	Low	Ultra-Low Power Sensor
Dynamic Current Gating	Low	Depends on switching	Moderate	Intermittent Work System
Differential and Current Mirror Optimization	Moderate	Significant	Mid-to-high	High-precision measurement
Power Isolation and Filtering	Moderate	Significant	Moderate	Mixed-signal chip
Event-driven self-calibration	Low average	High (long-term)	High	Applications requiring long-term stability

4. Further development of temperature compensation of the BGR development trend analysis

As more advanced high-order temperature-compensated BGRs are developed in the future, digital assistance and self-calibration technologies provide a new avenue of overcoming non-idealities and variation in processes in devices. Digital control and post-calibration can be included, therefore, in the design to reduce performance degradation due to system static mismatch and dynamic environment changes to a limited degree and, consequently, to increase robustness performance under real-world practice applications [11]. With constant innovations of new semiconductor and piezoelectric ceramic materials (including ALBeO), constant development of CMOS process, and implementation of SoC chips, high-order temperature-compensated bandgap reference circuitry will develop in a complex convergence of concepts, material composites, and system assembly. This development makes them an essential enabling technology to the next-generation high-precision electronic equipment.

5. Conclusion

The paper presents the trends in developing BGR circuits. BGR Compensations This compensation works well to counter first-order temperature drift, but higher-order compensations to counter reference voltage errors over wider temperature variations. The different circuit designs and compensation methods advocated in literature have attained great strides in accuracy, which proves that high-order compensation is the way forward in improving the performance at the base. Studies of circuits in high-order temperature-compensation bandgap reference have provided significant results, although more advances are required in cost of implementation, robustness of processes and systematical integration. Research into the combination of practicality and precision of process should be considered to advance the application of high-accuracy reference circuits high precision reference circuits into practice in other areas in the future.

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