A Modified Method for Compensating the Base-Emitter Voltage Used in Bandgap References

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Summary

In this paper after a survey on base structure of band gap references, the nonlinear property of VBE and its effect on thermal dependency in bandgap references has been discussed. Furthermore, one of the main methods of curvature correction has been investigated by using mathematical computations. The mathematical and circuit simulations have been implemented in MATLABR2007 and ADS2006, respectively. A corrected modified criterion has then been suggested to minimize the curvature of VBE by using the best available resistors according to the thermal variations of the collector currents. Accuracy of the introduced criterion has been confirmed by applying circuit simulations.

Key words:
Compensating, Bandgap References

1. Introduction

Voltage and current references with low dependence on thermal situation have been used in many analogue circuits. The more necessity of accuracy in these circuits the more thermal stability is in needed [1]. Since the second order non linearity of the function $V_{BE}(T)$ is generally the main limitation on the accuracy of bandgap references, it is necessary to minimize this nonlinearity. In [2] thermal dependency of resistors has been used to generate a temperature dependence collector current to compensate the nonlinearity of V_{BE}. In [3] the resistors with negative thermal coefficient have been suggested to linearize V_{BE}. Some of the researchers have suggested using the exponential currents to linearize the V_{BE}. [4], [5].

In this paper after a survey on nonlinearity of V_{BE} as the most important reason that decreases the accuracy in bandgap references, a new criterion will be introduced that minimizes the nonlinearity of V_{BE} using the selection of the best available resistors.

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2. Basic Structure of Bandgap References

As we know, V_{BE} is a voltage reference with negative thermal coefficient called CTAT (complementary to absolute temperature)[6], therefore it is reasonable to add it to a voltage reference with positive thermal coefficient or PTAT (Proportional to absolute temperature),this voltage is obtainable using the relation 1.

$$\begin{aligned}&\Delta V_{BE}(T)\\&=V_T\ln\left(\frac{I_{C2}}{I_{S2}}\right)-V_T\ln\left(\frac{I_{C1}}{I_{S1}}\right)\\&=V_T\ln(r)\\&=\frac{kT}{q}\ln(r)=K'T\rightarrow PTAT\end{aligned}\qquad(1)$$

This PTAT voltage is added to the CTAT voltage using the relation 2 which illustrated in Fig.1 [7].

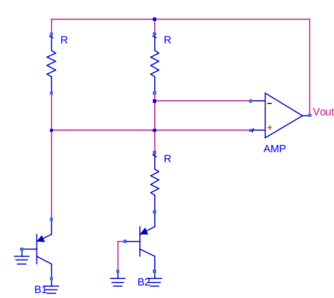


Figure 1. Basic structure of a bandgap reference

$$\begin{aligned}&V_{out}=(R_2+R_3)\times\frac{\left(V_{BE_1}-V_{BE_2}\right)}{R_3}+V_{BE_2}\\&=\alpha\Delta V_{BE}+V_{BE_2}=a.PTAT+CTAT\end{aligned}\qquad(2)$$

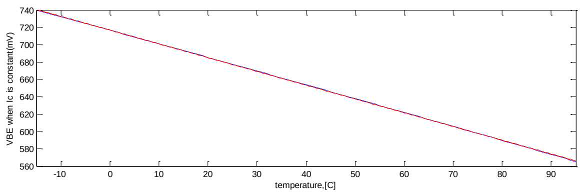
As a result by proper selection of a according to the proper adjusting of resistor proportions, the voltage reference with thermal stability can be obtained. However since PTAT is completely linear and CTAT is nonlinear Vref has a nonlinear curvature.

3. Nonlinearity of V_{BE}

According to the relevance between V_{BE} and physical parameters of transistor, different quantitative relations has been extracted which one of them is Meijer relation which described in equation 3[8].

$$V_{BE}(I_C,T)=\frac{KT}{q}Ln\left[\frac{I_C}{I_S(T)}\right] \qquad (3)$$
$$I_S(T)=C_M T^{\eta M} e^{\frac{-qV_M}{KT}}$$

This paper simulations have been done according to this relation. Fig.2 illustrates the V_{BE} variations when the temperature changes.



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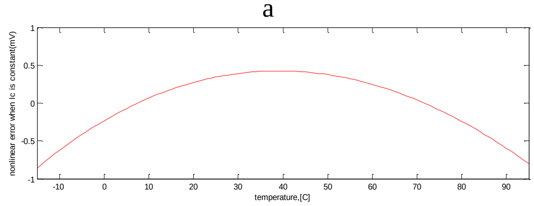

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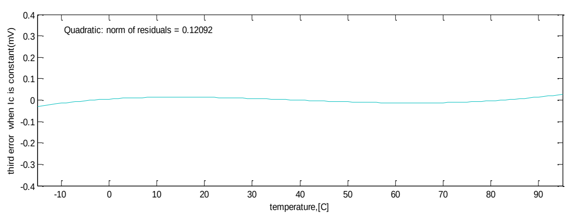

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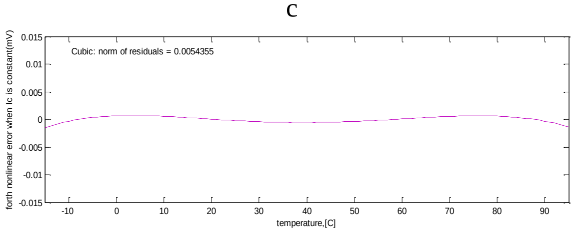

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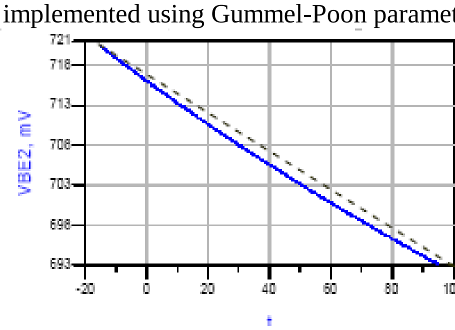
Figure 2. a-V_{BE} vs temperature, b-second order nonlinear error of V_{BE}, c- Third order nonlinear error of V_{BE}, d- forth order nonlinear error of V_{BE}

As clearly extracted from Fig.2-a, the difference between V_{BE} and linear curve fitted on it is little. For more clarity, Fig.2-b shows second order nonlinear error of V_{BE}, Fig.2-c and Fig.2-d shows third and forth nonlinear error of V_{BE}.

Assuming I_C independent from temperature, the Taylor polynomial of V_{BE} around T0 can be written as relation 4.

$$\begin{aligned} V_{BE}(T) &\approx V_{BE}(T_0) \\ &+\frac{k}{q}\left(\ln\left(\frac{I_C}{C_M}\right)-\eta_M\left(\ln(T_0)+1\right)\right)(T-T_0) \qquad (4) \\ &+\eta_M\frac{k}{q}\sum_{n=2}^{N}\frac{(-1)^{n+1}}{n(n-1)}\left(\frac{1}{T_0^{n-1}}\right)(T-T_0)^n \end{aligned}$$

Using the different error relations such as Lagrange error relation and also Fig.2-b to Fig.2-d shows that the second order nonlinear error is the most important reason of V_{BE} nonlinearity [8]. In order to study V_{BE} characteristics, different thermal ranges have been investigated until now [9].In this research, thermal range between -15 to 95 centigrade has been considered. Fig.5 shows the PTAT and CTAT voltage according to the simulation of circuit shown in Fig.1. The bipolar transistor used in the simulation has been implemented using Gummel-Poon parameters [10].



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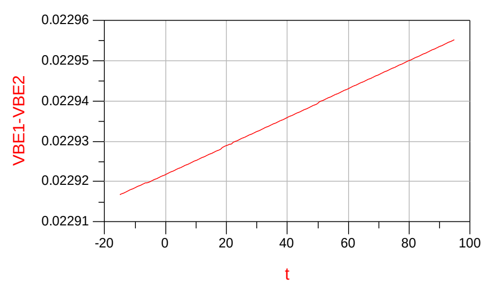

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Figure 3. a- CTAT voltage graph with obviously nonlinear curvature b- Linear PTAT voltage graph

As Fig.3 shows, CTAT is nonlinear while PTAT is linear; therefore, the aim is to overcome the problem of CTAT nonlinearity.

4. Curvature Correction of V_{BE}

According to the previous sections the aim is to minimize the nonlinearity of V_{BE}. The dependency of collector current to temperature can be used to overcome this problem. First of all the approach described in [8] is discussed briefly. Assuming the possibility of temperature dependent collector current, equation 5 has been considered.

$$V_{BE}(I_C,T)=\frac{KT}{q}Ln\left[\frac{I_C(T)}{I_S(T)}\right] \quad (5)$$

Meanwhile the second order derivation of V_{BE} as the most important reason of total nonlinearity has been obtained as relation 6.

$$V_{BE}^{(2)}(T)=\frac{k}{q}(2*\frac{1}{C_M}\frac{\partial I_C}{\partial T} + T\left(\frac{-1}{I_C^2}(\frac{\partial I_C}{\partial T})^2+\frac{1}{I_C}\frac{\partial^2 I_C}{\partial T^2}\right)-\eta_M*\frac{1}{T}) \quad (6)$$

Furthermore, it has been described that the difference of two base-emitter voltage related to two proportional collector currents remains PTAT even under thermal dependency of collector currents. Afterwards, The V_{BE} and its curvature have been studied for collector current as equation 7. The current of equation 7 can be obtained by applying a linearly temperature dependence voltage to a linearly temperature dependence resistor.

$$I_C=\frac{V_0[1+\alpha(T-T_0)]}{R_0[1+\beta(T-T_0)]} \quad (7)$$

In fact, if the $V_{BE}(T)$ is linear CTAT, according to linearity of PTAT it is possible to choose the proper coefficients in order to achieve a reference voltage without temperature dependency. If it is possible to make zero the second order derivation of $V_{BE}(T)$, the nonlinearity of $V_{BE}(T)$ will be eliminated. Therefore according to relations 6 and 7 the relation 8 is as following:

$$\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}=\frac{k}{q}\left\{2(\alpha-\beta)+T_0(\beta^2-\alpha^2)-\frac{\eta_M}{T_0}\right\} \quad (8)$$

This term will be made zero if the equation 9 is true.

$$\frac{k}{q}\left\{2(\alpha-\beta)+T_0(\beta^2-\alpha^2)-\frac{\eta_M}{T_0}\right\}=0$$
$$\Rightarrow \alpha^2T_0^{\,2}-2\alpha T_0+\eta_M+2\beta T_0-\beta^2T_0^{\,2}=0 \quad (9)$$

Keeping in the mind that β or the thermal coefficient of the transistors are known to us, $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ that is a parabola of α will be made zero if we could realize equation 10.

$$\alpha_{1,2}=\frac{1\pm\sqrt{1-\left(\eta_M+2\beta T_0-\beta^2T_0^{\,2}\right)}}{T_0} \quad (10)$$

In order to have real values for $\alpha_{1,2}$ it is necessary to have relation 11.

$$\beta\le\frac{1-\sqrt{\eta_M}}{T_0} \quad or \quad \beta\ge\frac{1+\sqrt{\eta_M}}{T_0} \quad (11)$$

For instance if $\eta_M=3$ and $T_0\approx 27^\circ C$, it is necessary to have

$$\beta\le -2440/2\,ppm/^\circ C$$
$$or \quad \beta\ge 9106/8\,ppm/^\circ C \quad (12)$$

In other words for all β satisfying the above conditions, it is possible to select some α making $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ zero. Plotting the curves by using MATLAB, this issue has been illustrated in Fig.4.

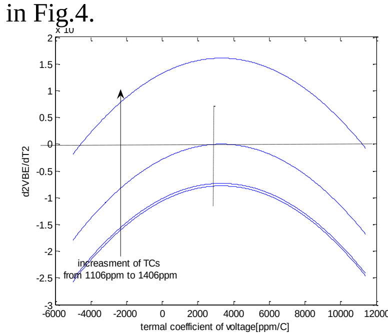


Figure 4. variation of second order derivation of V_{BE} with α,dashed line showes the place that second order derivation of V_{BE} gets zero and dotted showes the place that second order derivation of V_{BE} minimizes when β changes from 1106ppm/C to1406ppm/C

The available resistors cannot satisfy our requirement to make $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ zero and this term always remains negative. Considering β as a constant, the minimum value of $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ occurs when $\alpha=\frac{1}{T_0}$ as shown below.

$$\left(\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}\right)'=0\Rightarrow\alpha=\frac{1}{T_0} \quad (13)$$

Setting $\alpha=\frac{1}{T_0}$ means that applied voltage to the resistor corresponding to β must be in the form of $V=V_0\frac{T}{T_0}$ or PTAT and therefore the current of the transistor must be PTAT/R and using PTAT/R current had been noteworthy [8].

5. Selection of the Best resistor for Curvature Correction

5.1. A Survey on Present criterion

As discussed in the previous sections, resistors with β that make $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ zero are not available. Therefore it is necessary to look for the resistors that minimize $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$. Since PTAT/R current is typically used in most applications, by setting $\alpha = \frac{1}{T_0}$ we have

$$\frac{\partial^2 V_{BE}(T_0)}{\partial T^2} = \frac{k}{q}\left\{T_0\beta^2 - 2\beta + \left(\frac{1-\eta_M}{T_0}\right)\right\} \qquad (14)$$

Therefore to make $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ zero, the following equation has to be established.

$$\beta = \frac{1 \pm \sqrt{\eta_M}}{T_0} \qquad (15)$$

The ordinary method used is to select the resistor with β_k that minimizes criterion d_k defined as follows [8].

$$d_k = \min\left\{\left|\beta_k - \frac{1-\sqrt{\eta_M}}{T_0}\right|, \left|\beta_k - \frac{1+\sqrt{\eta_M}}{T_0}\right|\right\} \qquad (16)$$

5.2. New Recommended Criterion

The criterion d_k mentioned in the last section cannot minimize $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ strictly and some other resistors may exist that lead to smaller values of $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ and also there may some resistors that lead to equal d_k but different $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$. In other words, the variation of d_k according to relation 16 has been illustrated in Fig. 5.

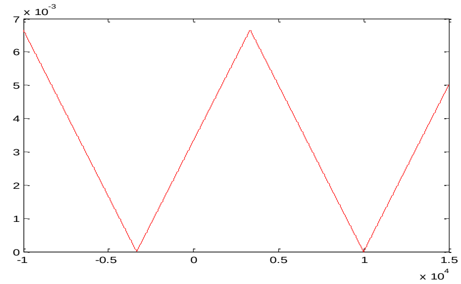


Figure 5. variation of d_k vs β according to relation 16

Therefore it is necessary to use more exact equations. In fact, assuming that we have different β_k and according to relation 14 and Fig. 6, it is obvious that those β_k have the best performance that the differences between $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ resulted from them and $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$ resulted from ideal β are minimums. That is the criterion dk must be defined as relation 17.

$$\begin{aligned} d_k &= \left.\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}\right|_{\beta_{ideal}} - \left.\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}\right|_{\beta} \\ &= \frac{k}{q}\left\{T_0\beta_{ideal}{}^2 - 2\beta_{ideal} + \left(\frac{1-\eta_M}{T_0}\right)\right\} - \\ &\quad \frac{k}{q}\left\{T_0\beta_k{}^2 - 2\beta_k + \left(\frac{1-\eta_M}{T_0}\right)\right\} \\ &= \frac{k}{q}\left\{T_0(\beta_{ideal}{}^2 - \beta_k{}^2) - 2(\beta_{ideal} - \beta_k)\right\} \end{aligned} \qquad (17)$$

Therefore minimizing d_k by the new criterion described in relation (18) leads to minimum value of $\frac{\partial^2 V_{BE}(T_0)}{\partial T^2}$.

$$\begin{aligned} d_k = \min\Bigg(&\left|(\beta_{ideal1}{}^2 - \beta_k{}^2) - \frac{2}{T_0}(\beta_{ideal1} - \beta_k)\right|, \\ &\left|(\beta_{ideal2}{}^2 - \beta_k{}^2) - \frac{2}{T_0}(\beta_{ideal2} - \beta_k)\right|\Bigg) \end{aligned} \qquad (18)$$

Where

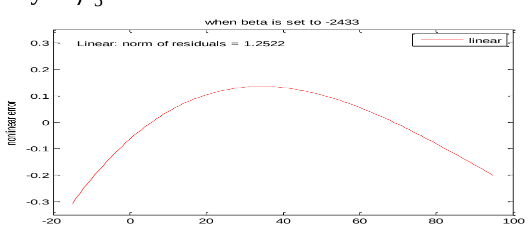
$$\beta_{ideal1} = \frac{1-\sqrt{\eta_M}}{T_0} \qquad , \beta_{ideal2} = \frac{1+\sqrt{\eta_M}}{T_0}$$

It is noticeable that this new criterion confirms the example discussed in [8]. In other words as table1 implies, both previous and new criterions confirm that the best result among the first to the forth group of resistors is achieved if the collector current is generated by applying a PTAT voltage to a resistor of the fourth group.

TABLE I. DETERMINATION OF d_k IN ORDER TO SELECT THE BEST RESISTOR, WHERE $\beta_{ideal1} = -3333/C$ AND $\beta_{ideal2} = 10000\,ppm/C$

β_k	Minimum of d_k according to relation 16	Minimum of new defined d_k according to relation 18
$\beta_1 = 1000\,ppm/C$	0.0043	0.0000390
$\beta_2 = 600\,ppm/C$	0.0039	0.0000369
$\beta_3 = -600\,ppm/C$	0.0027	0.0000289
$\beta_4 = -1000\,ppm/C$	0.0023	0.0000256
$\beta_5 = -2333\,ppm/C$	0.001	0.0000123
$\beta_6 = -4333\,ppm/C$	0.001	0.0000143

Fig.6 shows the nonlinear curvature corresponding to $\beta_5 = -2333\,ppm/C$ and $\beta_6 = -4333\,ppm/C$. Attention to this figure confirms the efficiency of new commended dk. in fact as table 1 implies, the previous criterion led to similar result for both β_5 and β_6 while Fig.6 ,clearly shows that this inference is not true. However, the new defined d_k (relation 18) predicts the difference between β s very well and selects β_5 as better selection. However, base-emitter voltage cannot be linear completely even in use of β_{ideal}. This problem is because of higher order derivations existence. According to the simulations shown in Fig.6, it is obvious that minimizing dk is equivalent to minimizing the nonlinear curvature. In general, simulations are in agreement with corresponding new dk. That is the difference from linear state about β_5 and β_6 are 1.25mV and 2.79mV respectively that confirms suitability of β_5.



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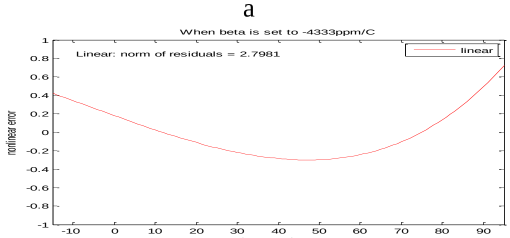

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Figure 6. nonlinear curvature of V_{BE} a-corresponding to $\beta_5 = -2333\,ppm/C$,b-corresponing to $\beta_6 = -4333\,ppm/C$

It is noticeable from Fig. 7 that a range of β can be assigned through applying the new d_k leading to a predetermined error by using a simple scale changing.

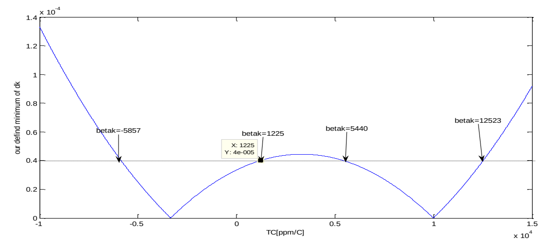

Figure 7. Variation of d_k with β using new commended d_k to determine the ranges of β that lead to given nonlinear error.

6. Conclusion

In this paper, after a survey on nonlinear property of V_{BE} and its effect on thermal dependency of bandgap references, a new criterion has been introduced to select optimal thermal coefficient to reach the minimum curvature in V_{BE} by using the thermal changing of collector current. The accuracy of commended criterion has been confirmed by using circuit simulations.

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