Temperature Analysis and Modeling of Voltage Regulator Circuits in PSpice

Galia Marinova[1]

Abstract – **The paper proposes a methodology for temperature analysis and modeling of voltage regulator circuits in PSpice. Six voltage regulator circuits are analyzed using temperature sweep in PSpice. Output stabilized voltages and output voltage ripples are simulated in temperature area and then temperature models are formulated for each circuit. Based on the results and the models obtained, a comparative study of the six voltage regulator circuits is performed.**

Keywords – **Voltage regulator, Temperature models, PSPICE.**

I. Introduction

The paper proposes a methodology for temperature analysis and modeling of voltage regulator circuits in PSpice. Six voltage regulator circuits are analyzed using temperature sweep in PSpice. Output stabilized voltages and output voltage ripples are simulated in temperature area and then temperature models are formulated for each circuit. Based on the results and the models obtained, a comparative study of the six voltage regulator circuits is performed.

[1]Galia Marinova is with the Telecommunications Faculty, Technical University – Sofia, bul. "Kliment Ohridski" 8, 1000 Sofia, Bulgaria, E-mail: gim@tu-sofia.bg.

II. Methodology for Temperature Analysis and Modeling of Voltage Regulator Circuits in PSpice

Table 1 presents the Methodology for temperature analysis and modeling of voltage regulator circuits in PSpice which develops the methodology for analysis of voltage regulator circuits from [3].

III. Temperature Analysis of the Voltage Regulators Carachteristics

Following the methodology described in Section II six voltage regulator circuits from Fig1a to Fig.1f are analyzed with PSpice in time area with temperature sweep for 4 temperatures: 0ºC 25ºC 40ºC 70ºC. The voltage regulator circuits from Fig. 1 are studied in details in [1,2]. Two traces are drawn for each circuit and the curves obtained are presented on Figures 2 to 7:

- Stabilized output voltage in temperature area Vout(ΔTºC) – Fig. 2a,3a,4a,5a,6a,7a
- Output voltage ripple in temperature area ΔVout(ΔTºC) – Fig. 2b,3b,4b,5b,6b,7b

IV. Analysis of the Temperature Functions for the Voltage Regulators

This section studies the temperature dependence of the circuits from Fig.1.

TABLE I

METHODOLOGY FOR TEMPERATURE ANALYSIS AND MODELING OF VOLTAGE REGULATOR CIRCUITS IN PSPICE

Characteristics of the voltage regulator circuits	**Definition of the analysis used in PSpice**	**Graphical processing of the simulation results in PSPICE**	**Definition of the voltage regulator parameters through postprocessing functions**
Temperature characteristics of the voltage regulator circuit	Temperature analysis with temperature sweep .TEMP <list of t^oC>	- Tracing a family of transient curves for the output voltage at temperatures from the list Vout(t), <list of t^oC> Extracting the curve of output voltage as a function of temperature - Vout(t°C) - Extracting the curve of output voltage ripple as a function of temperature - ΔVout(t°C) By applying the option PERFORMANCE ANALYSIS for determining the value **YatX** from the trace of output voltage **Maxr(Vout,t1,t2)-Minr(Vout, t1,t2)**	Determining the dependence: - Linear, nonlinear or constant; - Directly or inversely proportional; Determining the variation of the output voltage in the temperature interval [$t°_{min}$, $t°_{max}$] : $\Delta Vout\ (t°_{min}-t°_{max}) = Vout(t°_{max})-Vout(t°_{min})$ and for the variation of the voltage ripple: $\Delta\Delta Vout(t°_{min}-t°_{max}) = \Delta Vout(t°_{max})-\Delta Vout(t°_{min})$ When linear temperature dependence is observed for the output voltage or the ripple, the temperature dependence is modeled by a linear equation.

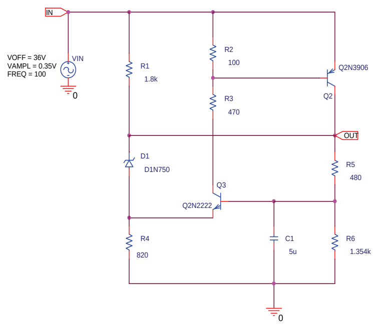

Fig. 1a. Linear voltage regulator with PNP pass transistor

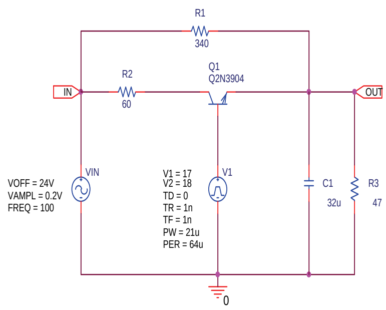

Fig. 1b. Voltage regulator with NPN pass transistor in switch mode

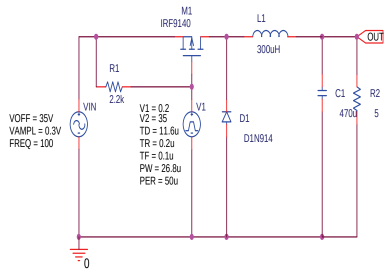

Fig. 1c. Buck DC-DC with MOS pass transistor in switch mode

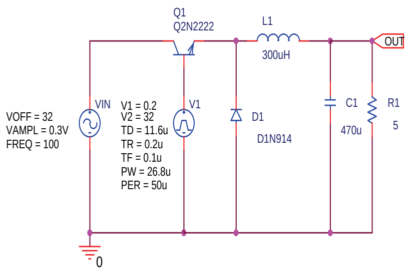

Fig. 1d. Positive buck regulator

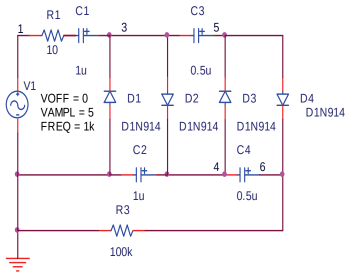

Fig. 1e. Cockcroft-Walton multiplying circuit

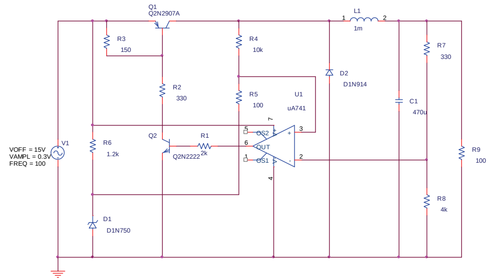

Fig. 1f. Buck switching regulator with PNP pass transistor and voltage translating circuit using op amp

Fig. 1. Six voltage regulator circuits

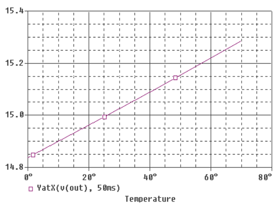

Fig.2a

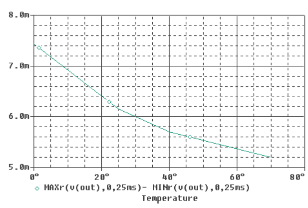

Fig.2b

Fig.2. Temperature curves for the circuit from Fig.1a

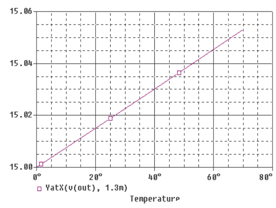

Fig.3a

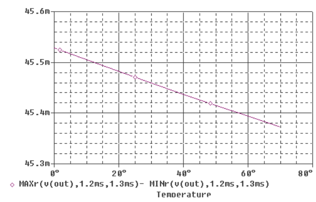

Fig.3b

Fig.3. Temperature curves for the circuit from Fig.1b

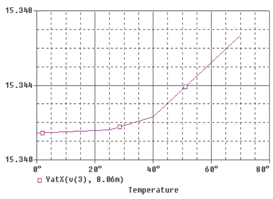

Fig.4a

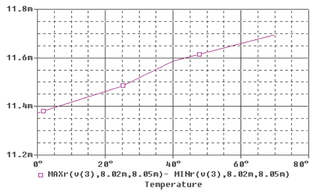

Fig.4b

Fig.4. Temperature curves for the circuit from Fig.1c

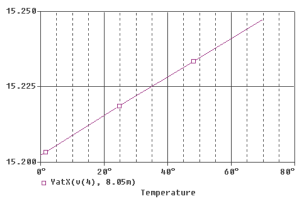

Fig.5a

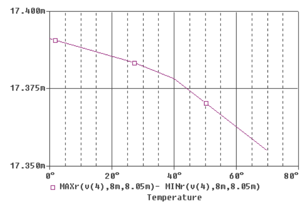

Fig.5b

Fig.5. Temperature curves for the circuit from Fig.1d

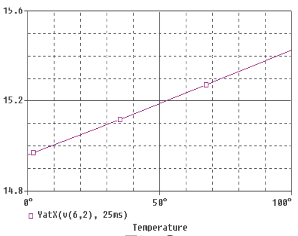

Fig.6a

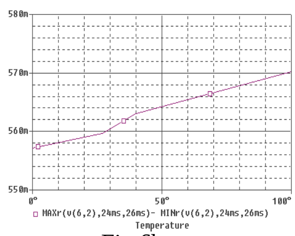

Fig.6b

Fig.6. Temperature curves for the circuit from Fig.1e

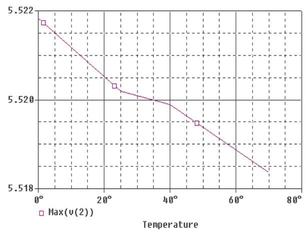

Fig.7a

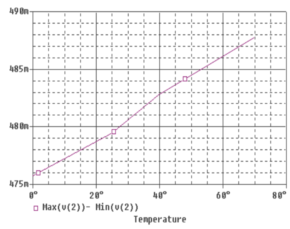

Fig.7b

Fig.7. Temperature curves for the circuit from Fig.1f

A. Temperature Functions for the Finear Voltage Regulator with PNP Pass Transistor

Considering Fig. 2a the stabilized output voltage of the linear voltage regulator with PNP pass transistor is linear and directly proportional function of temperature. The proportion observed is:

$$\Delta T°C=70°C \rightarrow \Delta Vout=0.447V$$

The coefficient of proportionality is determined as:

$$\frac{\Delta Vout}{\Delta T°C} = 6\frac{mV}{°C}$$

The formula of the temperature dependence for the output stabilized voltage of the circuit from linear voltage regulator with PNP pass transistor is:

$$\mathbf{V_{LIN}out(T°C)=(14.835+6.10^{-3}.T)V} \qquad \textbf{(1)}$$

Considering Fig.2b it's determined that the dependence of the stabilized output voltage ripple from temperature is nonlinear and the ripple variation is inverse to temperature variation. When the temperature increases the ripple decreases.

B. Temperature Functions for the Voltage Regulator with NPN Pass Transistor in Switch Mode

Considering Fig.3a it's determined that the stabilized output voltage of the voltage regulator with NPN pass transistor in switch mode is linear and directly proportional function of temperature. The proportion observed is:

ΔT°C=70°C → ΔVout=5mV

The coefficient of proportionality is determined as:

$$\frac{\Delta\Delta Vout}{\Delta T^{o}C} = 0.75\frac{mV}{^{o}C}$$

The formula obtained for the temperature dependence for the output stabilized voltage of the Voltage regulator with NPN pass transistor in switch mode is:

$$\mathbf{V_{SMNPN}out(T°C)=(15+0.75.10^{-3}.T)V} \qquad \textbf{(2)}$$

Considering Fig.3b it's determined that the dependence of the output voltage ripple from temperature for the Voltage regulator with NPN pass transistor in switch mode is linear and inversely proportional.The proportion observed is:

ΔT°C=70°C→ ΔΔVout= -0.14mV

The coefficient of proportionality is determined as:

$$\frac{\Delta\Delta Vout}{\Delta T°C} = -2\frac{\mu V}{°C}$$

The formula obtained for the temperature dependence of the output voltage ripple for the Voltage regulator with NPN pass transistor in switch mode is:

$$\mathbf{\Delta V_{SMNPN}out(T°C\ ) = (45.529 - 2.10^{-3}.T)mV} \qquad \textbf{(3)}$$

C. Temperature Functions for the Buck DC-DC

Considering Fig.4a it's determined that the stabilized output voltage of the Buck DC-DC slightly depends from temperature:

- $\mathbf{V_{MOS}out = (15.341 \div 15.342)V, T°C=0 \div 40°C}$
- V_{MOS}out increases with 5μV for temperature variation from 40°C to 70 °C

The temperature dependence of the stabilized output voltage of the Buck DC-DC can be expressed as follows:

$$\mathbf{V_{MOS}out \approx const = 15.34V \quad , \ T°C=0 \div 70°C}$$

Considering Fig.4b it's determined that the output voltage ripple of the Buck DC-DC depends very slightly from temperature and the dependence is close to linear and directly proportional. The proportion observed is:

ΔT°C=70°C→ ΔΔVout= -0.14mV

The coefficient of proportionality is determined as:

$$\frac{\Delta\Delta Vout}{\Delta T°C} = 2.3\frac{\mu V}{°C}$$

The formula obtained for the temperature dependence of the output voltage ripple for the Buck DC-DC is:

$$\mathbf{\Delta V_{MOS}out(T°C\ ) = (11.39 + 2.3.10^{-3}.T)mV} \qquad \textbf{(4)}$$

D. Temperature Functions for the Positive Buck Regulator

Considering Fig.5a it's determined that the stabilized output voltage of the positive buck regulator is linear and directly proportional function of temperature. The proportion observed is:

ΔT°C=70°C → ΔVout=45mV

The coefficient of proportionality is determined as:

$$\frac{\Delta Vout}{\Delta T°C} = 0.6\frac{mV}{°C}$$

The formula of the temperature dependence for the output stabilized voltage of the Positive buck regulator is:

$$\mathbf{V_{POS}out(T°C)=(15.202+0.6.10^{-3}.T)V} \qquad \textbf{(5)}$$

Considering Fig.5b it's determined that the temperature dependence of stabilized output voltage ripple of the positive buck regulator is nonlinear and the ripple variation is inverse to temperature variation. When the temperature increases the ripple decreases. For temperature variation from 0°C to 70°C the output voltage ripple decreases with 50μV.

E. Temperature Functions for the Cockcroft-Walton Voltage Multiplier

Considering Fig.6a it's determined that the stabilized output voltage of the Cockcroft-Walton voltage multiplier is linear and directly proportional function of temperature. The proportion observed is:

ΔT°C=70°C → ΔVout=0.328V

The coefficient of proportionality is determined as:

$$\frac{\Delta Vout}{\Delta T°C} = 4\frac{mV}{°C}$$

The formula of the temperature dependence for the output stabilized voltage of the Cockcroft-Walton voltage multiplier is:

$$\mathbf{V_{MULT}out(T°C) = (14.96 + 4.10^{-3}.T)V} \qquad \textbf{(6)}$$

Considering Fig.6b it's determined that the output voltage ripple of the Cockcroft-Walton voltage multiplier is close to linear and directly proportional function of temperature.The proportion observed is:

ΔT°C=70°C→ ΔΔVout= 9mV

The coefficient of proportionality is determined as:

$$\frac{\Delta Vout}{\Delta T°C} = 0.13\frac{\mu V}{°C}$$

The formula obtained for the temperature dependence of the output voltage ripple for the Cockcroft-Walton voltage multiplier is:

$$\mathbf{\Delta V_{MULT}out(T°C\ ) \approx (557 + 0.13.10^{-3}.T)mV} \qquad \textbf{(7)}$$

TABLE II

GENERALIZED DATA AND FORMULAS IN TEMPERATURE AREA FOR THE VOLTAGE REGULATORS

Voltage regulator circuit	**Stabilized output volatage as a function of temperature Vout(T°C)**	**Variation of the output voltage for temperature variation from 0°C to 70°C**	**Output voltage ripple as a function of temperature ΔVout(T°C)**	**Variation of the output voltage ripple for temperature variation from 0°C to 70°C**
Linear voltage regulator with PNP pass transistor	Linear, Direct proportional **$V_{LIN}out(T°C)=(14.835+6.10^{-3}.T)V$**	0.447V	Nonlinear, output voltage ripple vary in inverse direction than temperature	-2.1mV
Voltage regulator with NPN pass transistor in switch mode	Linear, Direct proportional **$V_{SMNPN}out(T°C)=(15+0.75.10^{-3}.T)V$**	5mV	Linear, Inverse proportional **$\Delta V_{SMNPN}out(T°C) = (45.529 - 2.10^{-3}.T)mV$**	-0.14mV
Buck DC-DC	Approximately constrant **$V_{MOS}out \approx const = 15.34V$**	6μV	Linear, Direct proportional **$\Delta V_{MOS}out(T°C) = (11.39 + 2.3.10^{-3}.T)mV$**	0.16mV
Positive buck regulator	Linear, Direct proportional **$V_{POS}out(T°C)=(15.202+0.6.10^{-3}.T)V$**	0.45V	Nonlinear, output voltage ripple vary in inverse direction than temperature	-50μV
Cockcroft-Walton multiplying circuit	Linear, Direct proportional **$V_{MULT}out(T°C) = (14.96 + 4.10^{-3}.T)V$**	0.328V	Approximately linear and direct proportional	9mV
Buck switching regulator with op amp	Approximately linear, Inverse proportional **$V_{OA}out(T°C) \approx (5.522 - 51.10^{-6}.T)V$**	-3.6mV	Linear, Direct proportional **$\Delta V_{OA}out(T°C) = (475 + 18.6.10^{-3}.T)mV$**	13mV

F. Temperature Functions for the Buck Switching Regulator with PNP Pass Transistor and Voltage Translating Circuit using Op Amp

Considering Fig.7a it's determined that the stabilized output voltage of the buck switching regulator with PNP pass transistor and voltage translating circuit using op amp is close to linear and inversely proportional function of temperature. The proportion observed is:

$$\Delta T°C=70°C \rightarrow \Delta Vout = -3.6mV$$

The coefficient of proportionality is determined as:

$$\frac{\Delta Vout}{\Delta T°C} = -51\frac{\mu V}{°C}$$

The formula of the temperature dependence for the stabilized output voltage of the circuit from Fig.1f is:

$$V_A out(T°C) \approx (5.522 - 51.10^{-6}.T)V \qquad (8)$$

Considering Fig.7b it's determined that the output voltage ripple of the Buck switching regulator with PNP pass transistor and voltage translating circuit using op amp is linear and directly proportional function of temperature. The proportion observed is

$$\Delta T°C=70°C \rightarrow \Delta\Delta Vout= 13mV$$

The coefficient of proportionality is determined as:

The formula obtained for the temperature dependence for the output stabilized voltage ripple of the circuit from Fig.1f is:

$$\Delta V_{OA}out(T°C) = (475 + 18.6.10^{-3}.T)mV \qquad (9)$$

V. GENERAL FORMULAS FOR THE TEMPERATURE FUNCTIONS OF THE VOLTAGE REGULATORS

Table 2 presents the generalized models and formulas in temperature area for the voltage regulators from Fig1a,1b,1c,1d,1e,1f.

VI. COMPARATIVE STUDY OF THE VOLTAGE REGULATORS BEHAVIOR IN TEMPERATURE AREA

The comparison of the data for the 6 voltage regulators is based on the modules of variations of the output voltage and

$$\frac{\Delta\Delta Vout}{\Delta T°C} = 18.6\frac{\mu V}{°C}$$

output voltage ripple in the temperature interval from 0°C to 70°C. The comparison of the modules of the output voltage variations is:

$\Delta V_{POS}out(T°C) > \Delta V_{LIN}out(T°C) > \Delta V_{MULT}ou(T°C) > \Delta V_{OA}out(T°C) > \Delta V_{SMNPN}ou(T°C) > \Delta V_{MOS}out(T°C)$

The positive buck regulator has the strongest temperature dependence of the stabilized output voltage and the buck DC-DC has the slightest temperature dependence.

The comparison of the variations modules of the output voltage ripples is:

$\Delta\Delta V_{OA}out(T°C) > \Delta\Delta V_{MULT}ou(T°C)$ t $>\Delta\Delta V_{LIN}out(T°C) > \Delta\Delta V_{MOS}out(T°C) > \Delta\Delta V_{SMNPN}out(T°C) > \Delta\Delta V_{POS}out(T°C)$

The Buck switching regulator with PNP pass transistor and voltage translating circuit using op amp has the strongest temperature dependence of the output voltage ripple and the positive buck regulator has the slightest temperature dependence.

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