The Electrothermal Ben-Yaakov Model of the Diode-Transistor Switch for an Electrothermal Analysis of BUCK Converters

Janusz Zarębski and Krzysztof Górecki

Abstract – **In the paper a new method of an electrothermal analysis of dc-dc converters operating in the steady-state is proposed. This method is based on the proposed by the authors electrothermal Ben-Yaakov model. This model was verified by comparison of SPICE simulated characteristics of the BUCK converter obtained by the proposed method and the electrothermal transient analysis.**

Keywords – **dc-dc converters, electrothermal analysis, SPICE**

I. INTRODUCTION

Important properties of dc-dc converters result from their characteristics corresponding to the steady-state. Due to the switched operation of the converter devices, such characteristics one can obtain from a transient analysis of the converter, e.g. by means of SPICE. Unfortunately, such an analysis can be unacceptably time-consuming, because of great differences between the period of the signal controlling a transistor switch (typically a power MOSFET) and the electrical time constants of the considered network, corresponding to RLC elements.

To shorten the time of the analysis (even a few thousand times), the average models of converters [1, 2, 3, 4] can be used.

One of the methods of formulating such models was proposed by Ben-Yaakov [1, 2]. After the implementation of a converter average model to SPICE, all characteristics of this circuit at the steady-state can be simulated using a dc analysis.

The converter average models described in the literature [1, 2, 3, 4] do not include a selfheating phenomenon existing in the semiconductor devices operating in the converter. As it was shown in [5, 6], selfheating can influence (even strongly) the converter characteristics.

In the paper, the modified form of the average Ben-Yaakov model of the diode-transistor switch being the main component of the average model of the PWM converter is proposed. This modification consists in including selfheating in the classical Ben-Yaakov switch average model, named here the electrothermal Ben-Yaakov model. The correctness of the new model was verified by comparison of SPICE simulation results obtained from both: the d.c. analysis using the electrothermal Ben-Yaakov model and the electrothermal transient analysis of the BUCK converter, operating in the continuous conducting mode.

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II. THE ELECTROTHERMAL BEN-YAAKOV MODEL

The classical Ben-Yaakov model of the diode-transistor switch is based on the piecewise-linear current-voltage models (characteristics) of the diode and the MOSFET (Fig.1a). In this figure, a transistor is modelled as a series connection of the ideal switch - controlled by the external controller and the resistance R_{ON} representing the MOSFET static drain-source on-state resistance, whereas the diode is represented by the ideal diode (Di), the voltage source (V_D) and the resistor (R_D), connected in series.

The five-terminal average model of the diode-transistor switch of the network form shown in Fig.1b has been worked out as averaging the time dependences of currents and voltages at the terminals of the considered devices. In Fig.1b the transistor is represented by the series connection of two controlled voltage sources (Er and Et), whereas the diode – by one controlled current source.

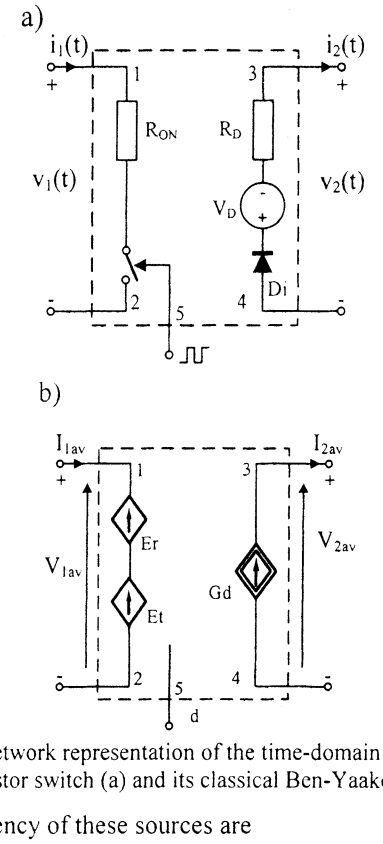

Fig.1. The network representation of the time-domain model of the diode-transistor switch (a) and its classical Ben-Yaakov model (b)

The efficiency of these sources are

$$Et = \frac{1-d}{d}\left(V_{2av} + V_D\right) \tag{1}$$

$$Er = \left(\frac{R_{ON}}{d} + \frac{(1-d) \cdot R_D}{d^2} \right) \cdot I_{1av} \quad (2)$$

$$Gd = \frac{1-d}{d} I_{1av} \quad (3)$$

where d denotes duty cycle factor, whereas the current I_{1av} and voltage V_{2av} are denoted in Fig.1b.

To perform an analysis of any dc-dc converter, the model from Fig.1b should replace the diode and the MOSFET, remembering that the nodes 1, 2, 5 have to be joined to the drain, source and the gate of the MOSFET, respectively, whereas the nodes 3, 4 – to the anode and cathode of the diode.

The change of the value of the duty cycle factor (d) in the range from 0 to 1 is performed by the change of the voltage at the node 5 in the range from 0 to 1 volt.

To include selfheating to the considered model (Fig.1b) the resistances R_{ON}, R_D and the voltage V_D have to be expressed as a function of the device inner (junction) temperature (T_{jT} for the transistor and T_{jD} for the diode, respectively) of the form

$$R_{ON} = R_{ON0} \cdot \left(1 + \alpha_{RON} \cdot \left(T_{jT} - T_a\right)\right) \quad (4)$$

$$R_D = R_{D0} \cdot \left(1 + \alpha_{RD} \cdot \left(T_{jD} - T_a\right)\right) \quad (5)$$

$$V_D = V_{D0} + \alpha_{UD} \cdot \left(T_{jD} - T_a\right) \quad (6)$$

where R_{ON0}, R_{D0} are the resistances corresponding to the ambient temperature (T_a), V_{D0} – the voltage across the forward biased diode at the ambient temperature, α_{RON} and α_{RD} – the temperature coefficients of the changes of R_{ON} and R_D resistances, respectively; whereas α_{UD} is the temperature coefficient of the changes of the diode voltage. The transistor and the diode junction temperatures are given by

$$T_{jT} = T_a + R_{thT} \cdot I_{1av} \cdot R_{ON} \cdot \frac{I_{1av}}{d} \quad (7)$$

$$T_{jD} = T_a + R_{thD} \cdot I_{2av} \cdot \left(V_D + R_D \cdot \frac{I_{2av}}{1-d} \right) \quad (8)$$

where R_{rhT} and R_{thD} denote the thermal resistances of the diode and the transistor, respectively.

The theoretical principles, indispensable to prove the equations (7 – 8) are described in [7]. As results from [7], at the high frequencies of switching the devices, their average inner temperature is a sum of the ambient temperature and a product of the device thermal resistance and the average value of the device dissipated power. In Eqs (7 – 8) the power dissipated only in the device ON-state is included, whereas the power during switching-time of the devices is omitted. Due to this simplification, the validity of the modified model is restricted to the situation, when the turn-on and the turn-off times are much less than the period of the switching signal.

III. Results

To verify the proposed model, the electrothermal characteristics of the BUCK converter (Fig.2) at the steady-state were simulated by SPICE. These characteristics are shown in Figs 3 – 5, where solid lines denote the results by the new model, points – the results by the electrothermal transient analysis with the use of the hybrid electrothermal device model [8, 9, 10] and dashed lines – the isothermal results by the classical Ben-Yaakov model [3].

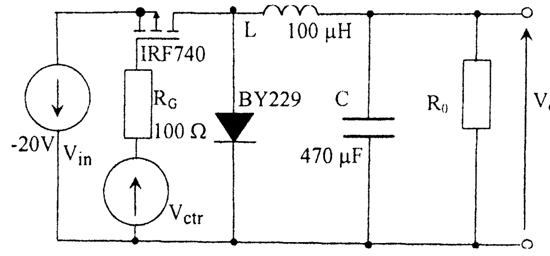

Fig.2. The BUCK converter under test

In the transient analysis the values of the device electrothermal hybrid models are from [8, 10]. In turn, in the classical Ben-Yaakov model: R_{ON}=0.6767 Ω, R_D = 0.12 Ω, V_D = 0.88 V, whereas in the model proposed in the paper the values of parameters $\alpha_{TT} = \alpha_{TD} = 3 \cdot 10^{-3}$ K^{-1}, α_{UD} =-2mV/K and $R_{thD} = R_{thT}$ = 20 K/W were additionally taken into account. The frequency of the switching signal, represented by the V_{ctr} source, is equal to 100 kHz.

In Fig.3 the dependence of the BUCK output voltage on the duty cycle factor for the fixed value of the output resistance R_0 = 3 Ω is presented. As seen, the curves obtained by the electrothermal transient analysis and by the electrothermal Ben-Yaakov model fit very well. Influence of selfheating is visible in the range of the higher values of the duty cycle factor. The differences between the isothermal and nonisothermal (without selfheating) characteristics at d = 1 are greater than 30%.

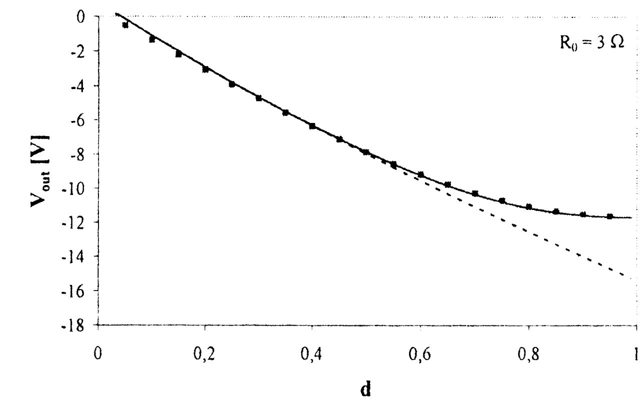

Fig.3. The dependence of the converter output voltage on the duty cycle factor

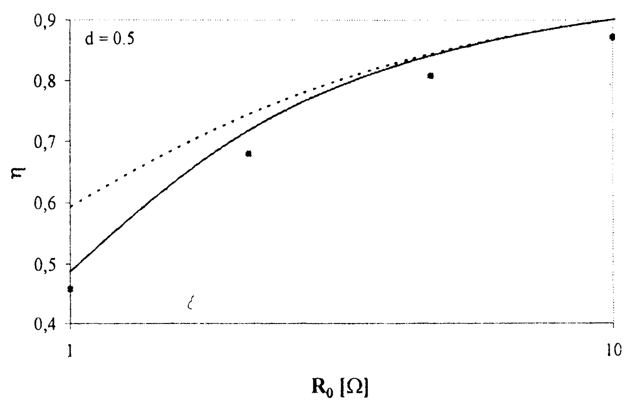

Fig.4. The dependence of the converter efficiency on the load resistance

In turn, in Fig.4 the dependence of the efficiency of the considered converter on the output resistance R_0 at d = 0.5, is shown. As seen, the isothermal characteristic differs from the nonisothermal ones even more than 20% (at $R_0 = 1\ \Omega$).

The calculated dependence of the temperatures T_{jT} and T_{jD} on the load resistance for the diode and the MOSFET are presented in Fig.5. As seen, the results obtained by both the electrothermal approaches are of a good agreement. The smaller value of the load resistance R_0 corresponds to the higher values of the devices inner temperature. Due to the restriction of the allowable temperature of the transistor (T_{jmax} = 150°C) the output resistance has to be greater than 2 Ω.

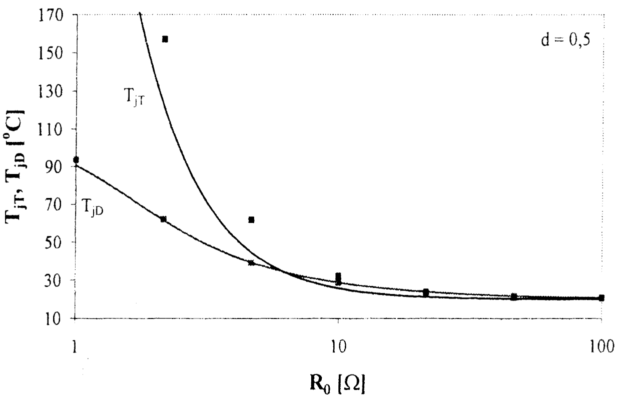

Fig.5. The dependences of the inner temperatures of the diode and the transistor on the load resistance

IV. Conclusions

In the paper the electrothermal Ben-Yaakov model of the diode-transistor switch including selfheating was proposed. Using this model allows performing the electrothermal analysis, at the steady-state, of any PWM converter operating in the continuous conducting mode.

The presented results of the analyses of the PWM buck converter confirm the correctness and usefulness of the proposed in this paper electrothermal Ben-Yaakov model.

The time of the analyses based on the electrothermal Ben-Yaakov model are typically less than 100 ms, whereas the electrothermal transient analysis needs much more time – even a few hours.

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