Integrated DC-DC Converter for IoT Applications

Tihomir Brusev[1], Georgi Kunov[2] and Elissaveta Gadjeva[3]

Abstract –**A low-power monolithic DC-DC converter for Internet of things (IoT) applications is presented in this paper. The maximum efficiency η of the circuit is 79.76%, when the input voltage is 3.6V while output voltage is regulated to be equal to 1.8V. The DC-DC converter is designed with Cadence on CMOS technology. The efficiency η of the circuit is investigated as a function of average output current. The reaction of the system is evaluated when the input voltage is changed in the range between 2.5V and 4.2V and the temperature varies from -50°C to 120°C.**

Keywords – **Cadence, CMOS technology, DC-DC converters, Integrated circuits, Internet of things (IoT).**

I. Introduction

The new fifth generation (5G) mobile network communication technology allows different type of sensors, electrical cars, electronic, automation and industrial devices to exchange data. Internet of thing (IoT) enables large number of embedded systems to be interconnected through the web. Using smartphones, tablets or computers the users can monitor and control different type of electronic devices in their offices and homes. The industry predicts that billions of components and systems will transmit data and receive instruction through the IoT [1].

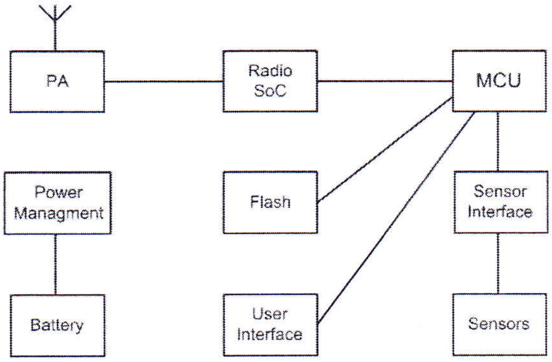

Fig. 1. Block circuit diagram of IoT wireless sensors network.

Power energy in industrial and home systems could be saved if IoT network technology is applied [2]. Appropriate operation time for electronic devices can be set in such way, that they could work after the peak energy demand. For this purpose different sensing and control techniques have to be chosen. Many devices connected in 5G network, like wireless motion and light sensors are powered through energy harvesting or battery power sources [3]. Some of them have to work without replacing the battery for years. The battery lifetime could be increased if the energy is used more efficiently.

The block circuit diagram of IoT wireless sensor network is shown in Fig. 1 [4]. The microcontrollers (MCUs) used for sensor monitoring and control have to work with low power consumption in order to save battery energy. Design of high efficiency DC-DC converters is the key for minimizing of power losses.

The power management system of wireless sensor devices connected in IoT is discussed in Section II*A* of this paper. The basic circuit's topologies of linear regulators and synchronous switching-mode DC-DC converters are considered in Section II*B* and Section II*C* respectively. Low-power monolithic BUCK DC-DC converter system designed on CMOS technology for IoT application is presented in Section III.

II. Theory

A. Battery powered wireless sensor networks

Wireless sensors connected in IoT networks have to be low energy consuming devices in order to be increased battery lifetime. They have to operate in most power efficient mode. Two different power management strategies for wireless sensors networks are shown in Fig. 2 [3]. Integrated BUCK DC-DC converter can help for decreasing of overall power losses [4].

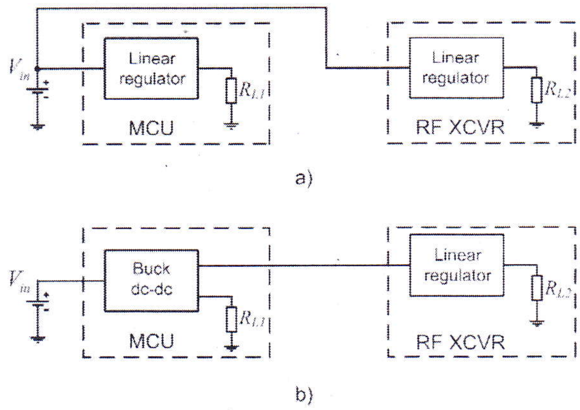

Fig. 2. Block circuit's diagrams for battery powered wireless sensors connected in IoT networks.

As it can be seen from the picture shown in Fig. 2a, linear regulators convert battery output voltage and ensure the desired input voltages of microcontroller (MCU) and high

[1]Tihomir Brusev is with the Faculty of Telecommunications, Technical University of Sofia, Kl. Ohridski 8, 1797 Sofia, Bulgaria, E-mail: brusev@ecad.tu-sofia.bg.
[2]Georgi Kunov is with the Faculty of Electronic Engineering and Technologies, Technical University of Sofia, Kl. Ohridski 8, 1797 Sofia, Bulgaria, E-mail: gkunov@tu-sofia.bg.
[3]Elissaveta Gadjeva is with the Faculty of Electronic Engineering and Technologies, Technical University of Sofia, Kl. Ohridski 8, 1797 Sofia, Bulgaria, E-mail: egadjeva@tu-sofia.bg.

frequency transceiver (RF XCVR). In the second power management strategy presented in Fig. 2b, monolithic BUCK DC-DC converter is used to deliver the input voltage MCU. Thus the first linear regulator from the block diagram shown in Fig. 2a is replaced with more power efficient circuit. The switching-mode converter also ensures the input voltage of second linear regulator. Therefore overall power losses of the wireless sensors, connected in IoT networks, are minimized.

B. Linear regulators

Linear regulators are simple electronic circuits which convert higher input to smaller output dc voltage [5]. These devices use small number of electronic components. The schematic of a linear regulator is shown in Fig. 3. Their advantage in integrated circuits applications is that they occupy small silicon area.

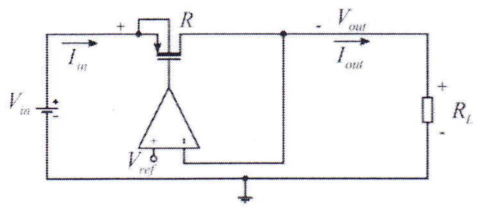

Fig. 3. Schematic of linear regulator.

Usually linear regulators use at least one transistor to control the desire dc level of output voltage. Their theoretical maximum possible efficiency is equal to:

$$\eta_{\max} = \frac{V_{out}}{V_{in}}, \tag{1}$$

where V_{out} is the dc output voltage, while V_{in} is the dc input voltage of linear regulator. In practice this maximum value cannot be achieved, because there are power losses in the series connected switch and in the parasitic impedances of the feedback circuit. A lot of waste heat is generated in linear regulators, which is a disadvantage of these circuits. This energy must be dissipated using radiators. Also when the difference between the input and the output voltage is large, linear regulators indicate low efficiency results.

C. Integrated BUCK DC-DC converters

The real synchronous BUCK DC-DC converters are circuit which could indicate high efficiency results η of about 90 %. Compared to the basic regulator's architectures the voltage drop of the diode in their structure is eliminated. Therefore they are suitable choice for low-power integrated circuit application. The efficiency η of the BUCK converter is equal to:

$$\eta = \frac{P_{out}}{P_{in}}, \tag{2}$$

where P_{out} is the average output power and P_{in} is the average input power of the DC-DC converter. The schematic of synchronous BUCK DC-DC converter is shown in Fig. 4. The energy losses are equal to the difference between the input and output average powers. They are distributed mainly in the output transistors and in the filters of the circuit.

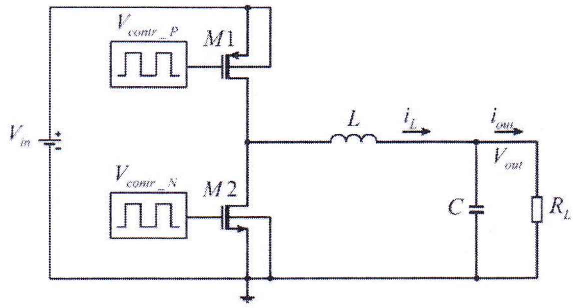

Fig. 4. Synchronous BUCK DC-DC converter.

Power losses in the transistors *M1* and *M2* dominate and have a major impact over the BUCK DC-DC converter's efficiency. They depend strongly on electrical circuit's parameters and are composed respectively of switching and conduction power losses [6]. The total power losses in MOS transistor can be further expressed by [7]:

$$P_{tot,MOS} = a\sqrt{\left(I^2 + \frac{\Delta i_L^2}{3}\right) f_s}, \tag{3}$$

where Δi_L is the inductor current ripple, f_s is the switching frequency, I is a dc current supplied to the load, and a is a coefficient depending on the equivalent series resistance of the transistors, the input total capacitance of the output MOS transistors and power supply voltage. The BUCK switching-mode DC-DC converters are more efficient circuits compared to the linear regulators. [8].

III. Low-power BUCK DC-DC converter designed on CMOS technology

The low-power integrated BUCK DC-DC converter is designed on CMOS technology with Cadence [9]. The block circuit's diagram is shown in Fig. 5.

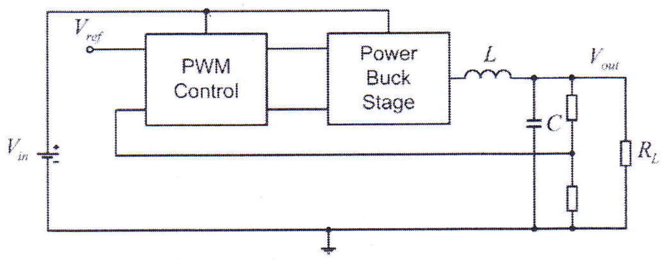

Fig. 5. Block circuit's diagram of PWM controlled BUCK DC-DC converter.

PWM control is used for regulation of the output voltage of the system. The input voltage of the BUCK converter is V_{in}=3.6V$_{dc}$ and the average output voltage is regulated to be equal to $V_{out\text{-}avg}$=1.8V [4]. The operating switching frequency

f_s of the system is 77MHz, while the corner frequency f_c of the output low-pass LC filter is selected to be 4.5MHz. High values of f_s and f_c are chosen in order to decrease the sizes of output inductor and capacitor of the circuit. Thus low-pass filter can be integrated on the chip and the occupied silicon area is minimized. The received results for the efficiency η as a function of average load current $I_{out\text{-}avg}$ of the designed BUCK converter are presented in Table I. The maximum efficiency η of the circuit equal to 79.76% is achieved when the load current $I_{out\text{-}avg}$ is 50mA.

TABLE I
EFFICIENCY OF BUCK CONVERTER AS A FUNCTION OF $I_{OUT\text{-}AVG}$

R_L [Ω]	BUCK DC-DC Converter	
	$I_{out\text{-}avg}$ [mA]	Efficiency [%]
10	180	63.3
15	120	72.8
25	72	78.75
36	50	79.76
50	36	78.7
100	18	70.72
180	10	59
250	7	51
360	5	42.5
900	2	23
1800	1	13

As it can be seen from the results presented in Table I, the efficiency of BUCK converter is decreased dramatically when the load current is smaller than 10mA. The efficiency of the BUCK DC-DC converter as a function of the average output current $I_{out\text{-}avg}$ is presented graphically in Fig. 6.

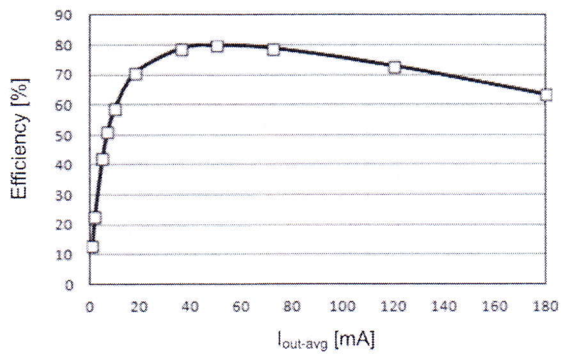

Fig. 6. Efficiency of the BUCK DC-DC converter as a function of the $I_{out\text{-}avg}$.

The detailed block diagram of PWM control, formed by error amplifier, ramp generator, comparator and buffer, plus power BUCK stage is presented in Fig. 7. The BUCK DC-DC converter systems which use PWM control have worse efficiency at light-load conditions. From energy point of view the designed circuit indicate better efficiency at high load currents. The BUCK DC-DC converter has to ensure the desired input voltages for microcontroller (MCU) and the high frequency transceiver (RF XCVR), when the operating conditions are changed.

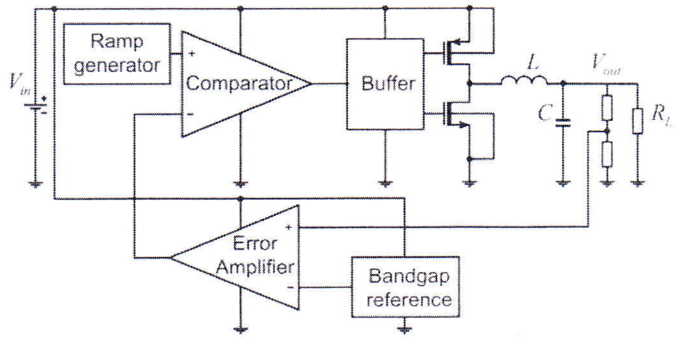

Fig. 7. PWM control circuit plus power BUCK DC-DC converter stage.

The waveform of DC-DC converter's output voltage V_{out} as a function of time is shown in Fig. 8. In this specific case the average value of the load current $I_{out\text{-}avg}$ is equal to 72mA.

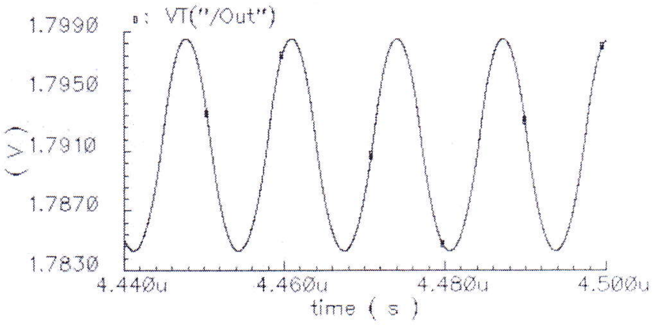

Fig. 8. The waveform of BUCK converter output voltage V_{out} as a function of time, when $I_{out\text{-}avg}$=72 mA.

The reaction of BUCK converter is estimated when input voltage varies from 2.5V to 4.2V. All the investigations are achieved at output current $I_{out\text{-}avg}$ equal to 50mA. The dependence of $V_{out\text{-}avg}$ as a function of V_{in} is illustrated in Fig. 9.

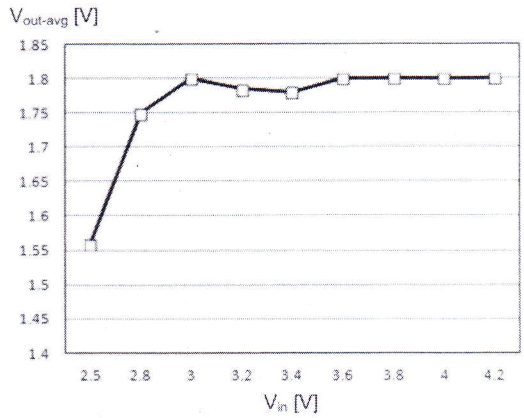

Fig. 9. Average output voltage $V_{out\text{-}avg}$ as a function of V_{in}.

As it can be seen from the picture, output voltage of BUCK converter $V_{out\text{-}avg}$ remains stable, when V_{in} varies between 2.8V and 4.2V. If the input voltage is changed in the range from 2.8V to 2.5V, $V_{out\text{-}avg}$ drops down with almost 0.2V.

Wireless sensors connected in IoT networks should display stable performance in wide temperature range. The schematic of the bandgap voltage reference is shown in Fig. 10. This circuit's topology provides a stable voltage for the whole converter system that is independent from the power supply, load current, and temperature variations [10].

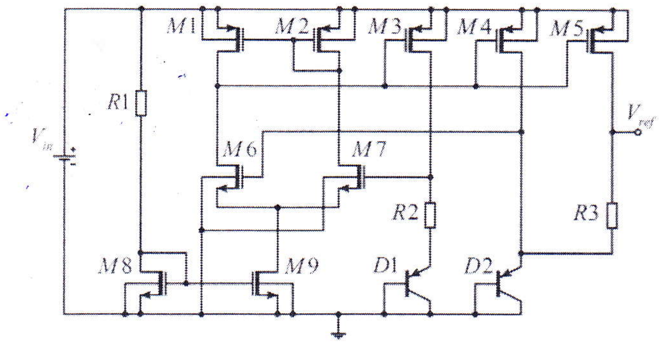

Fig. 10. Schematic of bandgap voltage reference.

The influence of the temperature over the circuit's parameters is investigated. The load current $I_{out\text{-}avg}$ is equal to 50mA, when BUCK DC-DC converter displays highest efficiency values. The received results of converter's average output voltage $V_{out\text{-}avg}$ and efficiency η at different temperatures are presented in Table II.

TABLE II

$V_{OUT\text{-}AVG}$ OF BUCK CONVERTER AS A FUNCTION OF THE TEMPERATURE

T [°C]	BUCK DC-DC Converter	
	$V_{out\text{-}avg}$ [V]	Efficiency [%]
-50	1.818	82.69
-25	1.817	81.59
0	1.813	79.93
25	1.8	79.76
40	1.796	78.72
60	1.787	77.73
80	1.775	80.05
100	1.764	76.13
120	1.76	76

The investigations show that when the temperature varies from -50°C to 120°C output voltage remain stable. As it can be seen from Table II $V_{out\text{-}avg}$ drops down from 1.82V to 1.76V with almost 0.06V.

The block circuit diagram illustrated in Fig. 2b is considered and the advantages of using the monolithic BUCK converter instead of linear regulator are estimated. The overall efficiency of the voltage regulators, shown in Fig. 2a and Fig. 2b respectively, are calculated and compared. In the calculation it is assumed that the linear regulators will work with maximum theoretical possible efficiency. The achieved investigation data, of the designed monolithic switching-mode circuit presented in this paper, are taken into account. The received results show that the integrated BUCK DC-DC converter increases the overall efficiency of voltage regulators presented in Fig. 2b with 35%, compared to the block circuit's diagram shown in Fig. 2a.

IV. CONCLUSION

Integrated BUCK DC-DC converter designed with Cadence on CMOS technology for IoT applications is presented in this paper. The circuit indicates better efficiency results at high load currents. The average output voltage $V_{out\text{-}avg}$ remains stable, when the input voltage V_{in} varies between 2.8V and 4.2V. The results show that when the temperature varies from -50°C to 120°C, the output voltage of the BUCK DC-DC converter is changed in the range between 1.82V and 1.76V. The maximum efficiency η of the circuit is 79.76%, when V_{in} is equal to 3.6V and $V_{out\text{-}avg}$ is regulated to be 1.8V. The advantages of using the integrated BUCK converter instead of linear regulator, in battery powered wireless sensors connected in IoT networks, are evaluated and estimated.

ACKNOWLEDGEMENT

The research described in this paper was carried out within the framework of BG05M20P001-1.001-0008-C01/28.02.2018.

REFERENCES

[1] M. Alhawari, D. Kilani, B. Mohammad, H. Saleh and M. Ismail, "An efficient thermal energy harvesting and power management for μWatt wearable BioChips", 2016 IEEE International Symposium on Circuits and Systems (ISCAS), Montreal, QC, pp. 2258-2261, 2016.

[2] www.silabs.com, *Overcoming Challenges of Connecting Intelligent Nodes to the Internet of Things*, 2012, Silicon Laboratories Inc.

[3] R. L. B. Zamparette, H. D. Klimach and S. Bampi, "A 90% efficiency 60 mW MPPT switched capacitor DC — DC converter for photovoltaic energy harvesting aiming for IoT applications", 2017 IEEE 8th Latin American Symposium on Circuits & Systems (LASCAS), pp. 1-4, Bariloche, 2017.

[4] www.keysight.com, *The big five IoT challenges*, issue 3, 2017.

[5] P. Hazucha, S. T. Moon, G. Schrom, F. Paillet, D. Gardner, S. Rajapandian, T. Karnik, "High Voltage Tolerant Linear Regulator With Fast Digital Control for Biasing of Integrated DC-DC Converters", IEEE Journal of Solid-State Circuits, vol.42, no. 1, pp.66-73, Jan. 2007.

[6] J. Ham, H. Jung, H. Kim, W. Lim, D. Heo and Y. Yang, "A CMOS Envelope Tracking Power Amplifier for LTE Mobile Applications", Journal of Semiconductor Technology and Science, vol. 14, no. 2, April 2014, pp. 235-245.

[7] V. Kurson, *Supply and Threshold Voltage Scalind Techniques in CMOS Circuits*, University of Rochester, NY, 2004.

[8] M. Hassan, L. Larson, V. Leung, and P. Asbeck, "A Combined Series-Parallel Hybrid Envelope Amplifier for Envelope Tracking Mobile Terminal RF Power Amplifier Applications", IEEE Journal of Solid-State Circuits, vol. 47, no.5, May 2012, pp. 1185-1198.

[9] www.cadence.com

[10] Y. Wu and V. Aparin, "A monolithic low phase noise 1.7GHz CMOS VCO for zero-IF cellular CDMA receivers", IEEE International Solid-State Circuits Conference (IEEE Cat. No.04CH37519), vol.1, pp. 396-535, 2004.