Towards a Design of DC Converter for the Internet of Things

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ABSTRACT: *Extensive research in many directions on the Internet of Things (IoT) is currently undertaken. In this research we studied the possibility of a low-power monolithic DC converter for applying in the IoT environment. We have specified the possible maximum efficiency of the circuits and the input as well as output voltage. Using the CMOS technology, we have designed the DC to DC converter. We studied the efficiency of the circuit as a function of average output current. The assessment exercises are evaluated when the input voltage is changed and we also observed the temperature variation during the process.*

1. 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].

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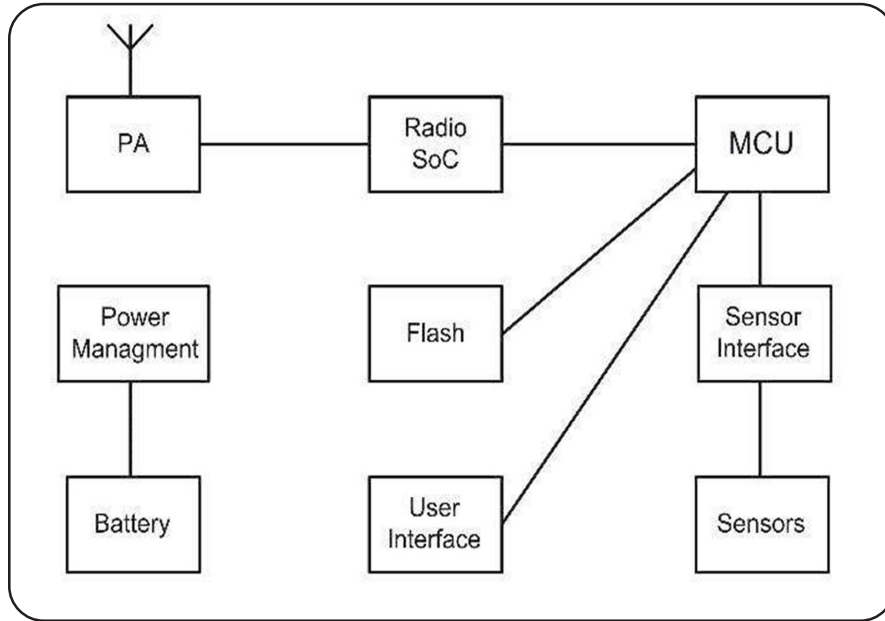
Figure 1. Block circuit diagram of IoT wireless sensors network

The power management system of wireless sensor devices connected in IoT is discussed in Section 2*A* of this paper. The basic circuit's topologies of linear regulators and synchronous switching-mode DC-DC converters are considered in Section 2*B* and Section 2*C* respectively. Low-power monolithic BUCK DC-DC converter system designed on CMOS technology for IoT application is presented in Section 3.

2. Theory

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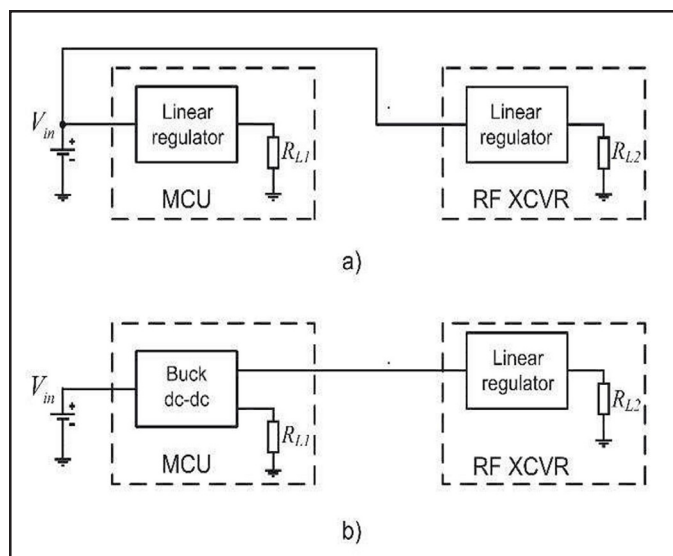

Figure 2. Block circuit's diagrams for battery powered wireless sensors connected in IoT networks

As it can be seen from the picture shown in Figure 2a, linear regulators convert battery output voltage and ensure the desired input voltages of microcontroller (MCU) and high frequency transceiver (RF XCVR). In the second power management strategy presented in Figure 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 Figure 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.

2.2. 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 Figure 3. Their advantage in integrated circuits applications is that they occupy small silicon area.
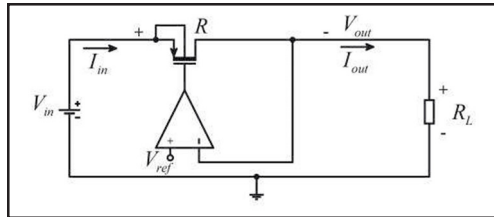

Figure 3. Schematic of linear regulator

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.

2.3. 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 Figure 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.
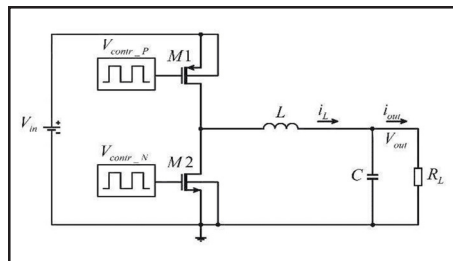

Figure 4. Synchronous BUCK DC-DC converter

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]:

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

where Δ_{iL} 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].

3. 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 Figure 5.
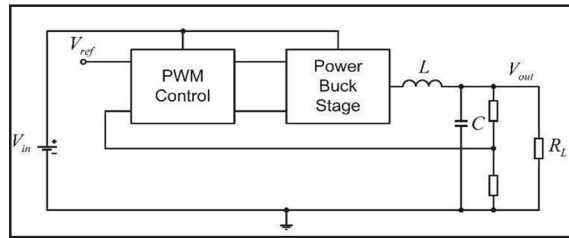

Figure 5. Block circuit's diagram of PWM controlled BUCK DC-DC converter

PWM control is used for regulation of the output voltage of the system. The input voltage of the BUCK converter is V_{in} = 3.6Vdc and the average output voltage is regulated to be equal to $V_{out-avg}$ = 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 $I_{out-avg}$ of the designed BUCK converter are presented in Table 2. The maximum efficiency η of the circuit equal to 79.76% is achieved when the load current $I_{out-avg}$ is 50mA.

RL[Ω]	BUCK DC-DC Converter	
	$I_{out-avg}$ [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

Table 1. Efficiency of Buck Converter as a Function of $I_{out-avg}$

As it can be seen from the results presented in Table 1, 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 Figure 6.
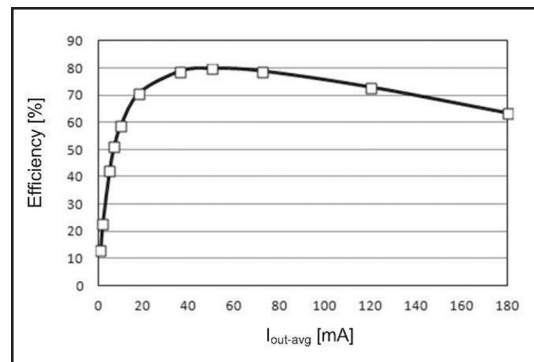

Figure 6. Efficiency of the BUCK DC-DC converter as a function of the $I_{out\text{-}avg}$

The detailed block diagram of PWM control, formed by error amplifier, ramp generator, comparator and buffer, plus power BUCK stage is presented in Figure 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 indicates 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.
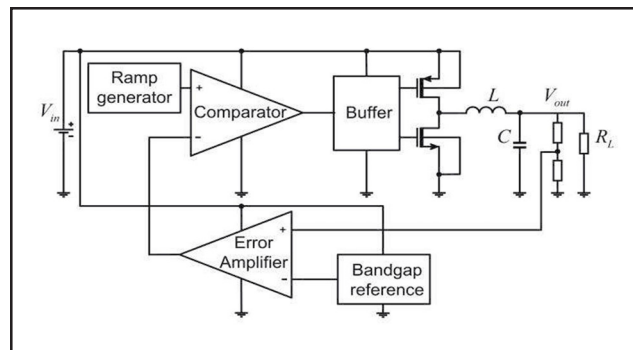

Figure 7. PWM control circuit plus power BUCK DC-DC converter stage

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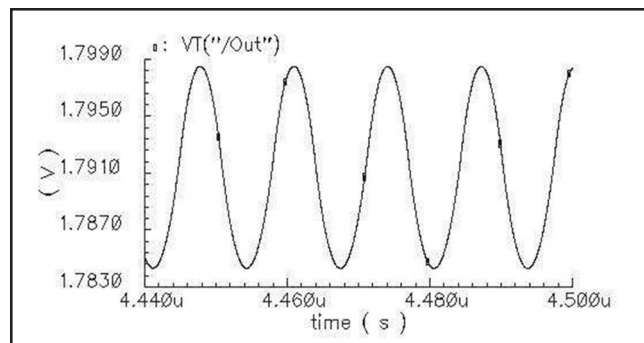

Figure 8. The waveform of BUCK converter output voltage V_{out} as a function of time, when $I_{out\text{-}avg}$ = 72 mA

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 Figure 9.
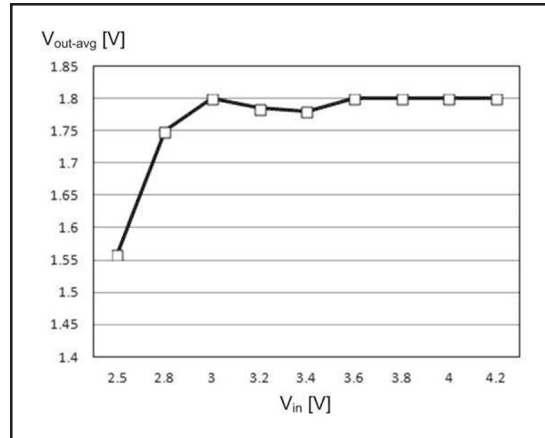

Figure 9. Average output voltage $V_{out\text{-}avg}$ as a function of V_{in}

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 Figure 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].
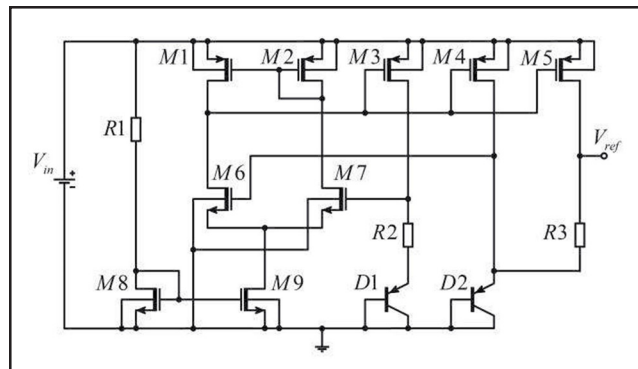

Figure 10. Schematic of bandgap voltage reference

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 2.

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 2 $V_{out\text{-}avg}$ drops down from 1.82V to 1.76V with almost 0.06V.

The block circuit diagram illustrated in Figure 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 Figure 2a and Figure 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

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

Table 2. $V_{out\text{-}avg}$ of Buck Converter as a Function of the Temperature

overall efficiency of voltage regulators presented in Figure 2b with 35%, compared to the block circuit's diagram shown in Figure 2a.

4. 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.

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