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High efficiency DC/DC converter for smart radiator valve

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***Abstract* — Smart Valve is the energy harvesting supplied solution with 100% participation in the market for heating radiator control. As today the EnOcean RF (Radio Frequency) standard is the only available RF protocol. Currently also Bluetooth and ZigBee versions are under development. For special radiators and floor heating systems a new electronic valve should be developed. It is based on the same energy saving components and design as the current valve actuator. Major difference in the new design is the usage of a 10 year long life battery for the valve supply. This enables companies to provide the Smart Valve also to radiators in rooms with little usage or other special requirements as basements, garages or housekeeping stock rooms. Also private users can use this valve actuators and control them by a smartphone, PC or tablet. As a result the proposed DC/DC converter will be used in real final product which must have the best price and efficiency ratio.**

***Keywords* — buck, DC/DC converter, energy harvesting, Smart Valve**

I. Introduction

The goal of this paper is developing cheaper and high efficiency DC/DC converter for battery powered radiator valve (Smart Valve). Battery used in this product will be special long life 9V battery manufactured by Dynamis. This battery has very low self-discharge and high density of energy with total capacity of 1300mAh. The battery is based on Li-MnO2 technology and has dimensions as a standard 9V battery. Over 10 years' service life of battery is guaranteed by the manufacturer. [1]

Battery voltage goes from 9.7V to 5.5V during lifetime. This value are input voltage range (VIN) for DC/DC converter. The important thing is that VIN voltage, never be higher than 10V.

Output voltage called VOUT is currently not exactly defined, because of the wide input voltage range of all components in Smart Valve but it should be between 2.5V and 3.5V.

As Smart Valve is based on energy harvesting product whole electronics like μC (micro Controller), RF module and motor is extremely efficient with sleep current around 5uA. However, in case of adjusting the position of radiator valve, current consumption can be increased up to 100mAh. It is clear that there are two types of loads. Light load around 5uA will be around 80% in10 years. For rest 20% of service life, current consumption will be from 30mAh to 50mAh. Proposed DC/DC converter must be optimized for both types of load. Which seems to be the main problem. The Second problem is that DC/DC converter will be part of mass produced product where price for components and assembly are very important. Also availability of all components must be guaranteed for next years.

The first problem can be solved by commercial design, however the second problem needs discrete design. Both solutions will be described and compared in this paper.

II. Common Types of DC/DC Converters

A. Linear Regulators

Linear regulators use linear, non-switching techniques to regulate the voltage output from the power supply as can be seen in figure (Fig. 1). The regulator's resistance varies according to the load and results in a constant output voltage. All linear regulators require an input voltage at least some minimum amount higher than the desired output voltage. That minimum amount is called the dropout voltage. A low-dropout or LDO regulator is a DC linear regulator which can regulate the output voltage even when the supply voltage is very close to the output voltage. Linear regulators are a great choice for powering very low powered devices or applications where the difference between the input voltage and the output voltage is small. They are a simple and cheap solution, but linear regulators are normally inefficient because the difference between the input voltage and regulated output voltage is continually dissipated as heat. [2]

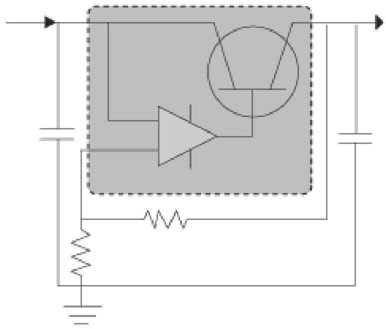

Fig. 1 Internal structure of linear regulator

B. Switching Regulators

Some of the key requirements of today's power management solutions include less power consumption under various load conditions, less space, high reliability and wide input voltage [3]-[6] These requirements are driving the need for highly efficient, wide VIN, low quiescent current (IQ) switching regulators in a broad range of applications. Switching regulators rapidly switches a series element on and off. They can operate with both synchronous and non-synchronous switches (FETs). These devices store the input energy temporarily and then releasing that energy to the output at a different voltage level. The switch's duty cycle sets the amount of charge transferred to the load. Switching regulators are efficient because the series element is either fully conducting or switched off so it dissipates almost no power. Switching regulators are able to generate output voltages that are higher than the input voltage or of opposite polarity, unlike linear regulators. The versatility of these converters allows configuration for buck, boost, buck-boost, flyback, inverting in isolated and non-isolated applications. Integrated FET regulators are a subset of switching regulators. These microcircuits have integrated the power MOSFET and are considered a whole solution; whereas controllers employ external power MOSFETs. Both configurations are classified as switching regulators because they regulate the output voltage. Basic topology of buck converter is shown in figure (Fig. 2). [2]

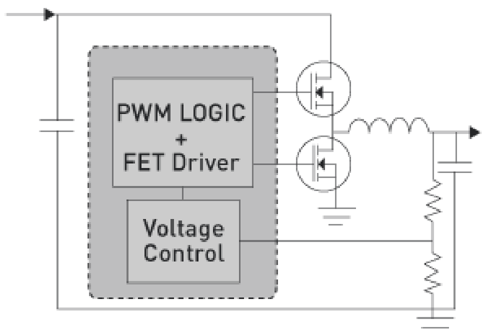

Fig. 2 Basic topology of buck converter

C. Comparison of linear regulators and switching regulators

Linear regulators are a great choice for powering very low powered devices or applications where the difference between the input and output is small. Even though they are easy to use, simple and cheap, a linear regulator is normally inefficient. The equation for dissipated power in a linear regulator is: **Power dissipation = (input voltage – output voltage) × load current**.

Switching regulators on the other hand, are highly efficient and available as modular chips, which are compact and reliable. Switching regulators can be further divided into isolated and non-isolated. [2]

Comparison between two mentioned regulators are shown in Table 1.

Table 1. Linear regulator vs. Switched regulator

	Linear Regulator	Switching Regulator
Design Flexibility	Buck	Buck, Boost, Buck-Boost
Efficiency	Normally low to medium-high for low difference between VIN-VOUT	High
Complexity	Low	Medium to high
Size	Small to medium, larger at high power	Smaller at similar higher power (depending on the switching frequency)
Total Cost	Low	Medium to high – external components
Ripple/Noise/EMI	Low	Medium to high
VIN Range	Narrow (depending on power dissipation)	Wide

III. COMMERCIAL SOLUTION

The first option was commercial design because the suggestion was that it has better efficiency with special buck converter. Furthermore, IC. It is because companies producing these ICs are spending much more time and sources of development. The goal is to find as efficient circuit as possible with thinking also on price. According to this goal the TPS62745 solution produced by Texas Instruments was selected as can be seen in figure (Fig. 3). [7]

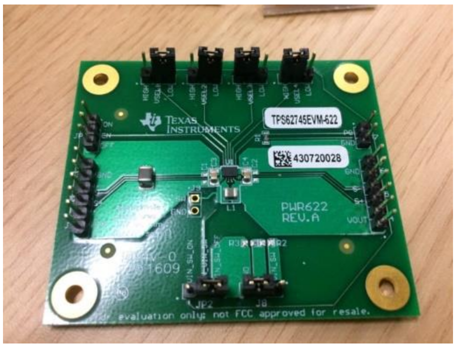

Fig. 3 Evaluation board TPS62745

The TPS62745 is a highly efficient, ultra-low power synchronous step down converter optimized for low power wireless applications. It provides a regulated output voltage consuming only 400-nA quiescent current. The device operates from two rechargeable Li-Ion batteries, Li-primary battery chemistries such as Li-SOCl2, Li-SO2, Li-MnO2 or four to six cell alkaline batteries. The input voltage range up to 10 V allows also operation from a USB port and thin-film solar modules. The output voltage is set with four VSEL pins between 1.8 V and 3.3 V for TPS62745 or 1.3 V and 2.8 V for TPS627451. TPS62745 features low output ripple voltage and low noise with a small output.

It fits all from main requirements:

• Input Voltage Range VIN from 3.3 V to 10 V

- Typical 400 nA Quiescent Current
- Up to 90% efficiency with load currents >15 μA
- Up to 300 mA Output Current RF Friendly

Schematic connection is shown in figure (Fig. 4).

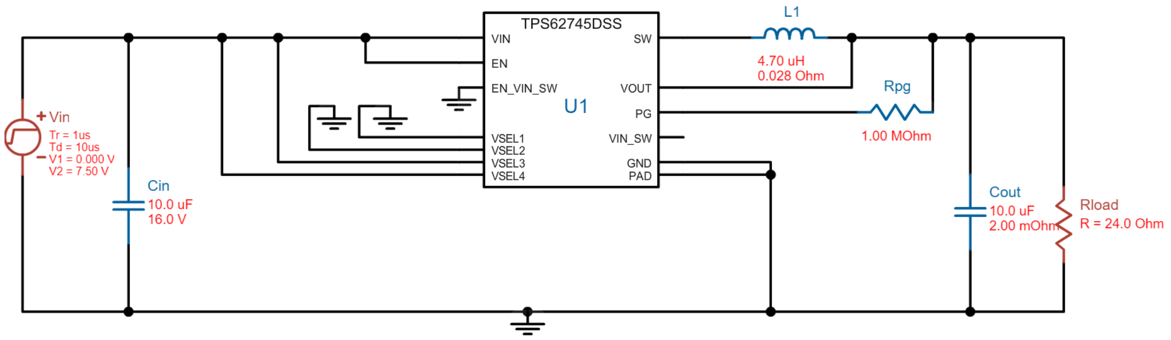

Fig. 4 Basic scheme of TPS62745

This is a highly integrated solution with only a few additional components. Input and output capacitor, inductor and one resistor. At this time it is solution with best efficiency, especially for small loads like 5uA (76% and can be optimized up to 90%). Real efficiency measurement (for detailed results, please see chapter V) was done on evaluation board TPS62745EVM-622 (S/N: 430720028) with BOM (Bill of Materials) as can be seen in Table 2.

Table 2. BOM list of TPS62745

		>1000 pcs [€]	1 pc [€]
U1	TPS62745	0.68	1.86
C1	10uF LMK212BJ106KG-T	0.02	0.13
C2	10uF LMK212BJ106KG-T	0.02	0.13
R1	1M RC0603FR-071ML	0.001	0.09
L1	4.7uH DFE252012P-4R7M	0.13	0.37
	TOTAL PRICE	0.851	2.58

All components were selected according to performance and manufacturer recommendation. Real efficiency was measured on Price 0.85EUR. The biggest issue is that manufacturers can discontinue this IC at any time, which should be a large problem in the future. This is the reason why the discrete solution is also parallel developments.

IV. Discrete Solution

From many points of view, discrete solution is a better choice for mass production, however performance never be as good as a commercial solution. This solution must be cheaper and consist of easy replaceable components like transistors and RLC components. Also control management must be done by internal μC. For comparison, a comparator and a discrete buck module was created which is shown in figure (Fig. 5).

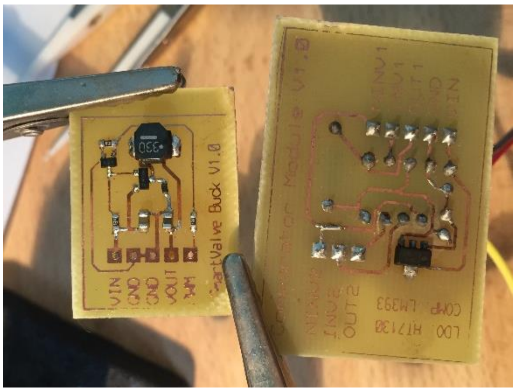

Fig. 5 Comparator and discrete buck module

A. Discrete Solution - Self-starting

From another point of view, the main problem is self-starting. If DC/DC converter will be switched by internal μC which will be supplied with power from same DC/DC converter the problem is that it cannot start by itself. The problem can occur after replacing battery. This issue can be solved by the cheap LDO with enable pin which can be switched off when discrete buck converter will start. Such LDO can be also used for some kind of hybrid power solution. From the theory of switched buck converter it is clear that they have a problem with light loads and they are not as effective as with higher loads. On the other hand linear power regulators have bad efficiency at higher loads due to the large thermal losses. In hybrid solution the LDO can be used for light loads and when efficiency curves will be crossed, buck converter can be switched as a main voltage regulator. Then final efficiency will be intersection between LDO and buck efficiency. This can be controlled directly by current sensing or like in this product by firmware. As it has a final number of loads the right power supply for each task can be selected. For example, before adjusting the position of radiator valve the buck converter will be chosen because the higher load is expected. After this task the LDO will be selected and the device will stay in sleep mode. This kind of control can simplify main firmware and save one ADC (Analog Digital Converter) pin for current sensing.

Another much simpler solution can be USB connector which is already included in product for debug purposes. As self-starting is required only after battery replacing. USB can be used as power supply and power up μC thought simple Zener diode. This is a cheap and simple solution, but from a customer point of view, it is not very user friendly.

Third but not last solution can be high-side switch operating in depletion mode. In a depletion-mode MOSFET, the device is normally ON at zero gate–source voltage. This will allow current flow to the μC which can start buck converter. This solution looks clever, however, implementation needs very fast μC reaction and of course overvoltage protection. Which is not suitable for this application according to price and total product efficiency.

B. Discrete Solution - Control

The second problem at discrete solution is control circuit. In general source of pulse width modulated signal like PWM is required. This can be achieved by three components: special IC called buck driver, by μC or by an analog regulation system composed from operational amplifier and clock generator like NE555.

The first method which uses buck driver has the same problems as the previously mentioned commercial solution. Also currently there is no any low-cost IC from major manufacturers. The analog solution needs a lot of additional components and final price is similar to a commercial solution. This means that best solution is use the μC. However the product is extremely low power device where μC control is not possible in all power modes. For this purpose an investigated solution which is using internal comparator in μC. This comparator has very low power consumption and it is working in all power modes. For simulation purposes the comparator was used as can be seen in figure (Fig. 6).

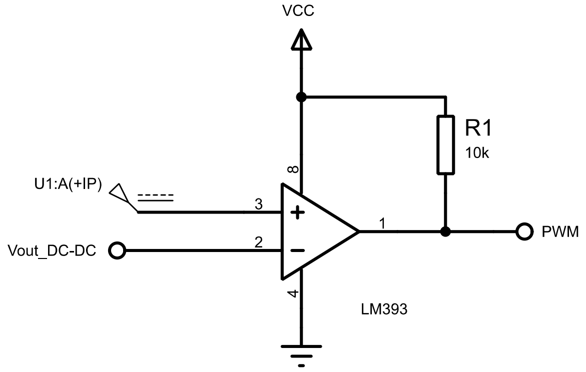

Fig. 6 Substitution of internal comparator for simulation purpose

The main problem is that it is only proportional regulation and as PWM signal is just the output from comparator it is really slow. The maximum frequency is around 8 kHz. This means that large inductance which is not available in the market for a good price is required. This is the reason why efficiency of discrete solution for more conditions are limited.

C. Discrete solution – Tested Topologies

At the beginning the standard buck topology was used. As high-side switching device was selected P-channel MOSFET with N-channel driver. This topology was next improved with gate driver composed of two bipolar transistors as can be seen in figure (Fig. 7). Topology for Synchronous buck converter was also tested. All topologies are still under investigation in ways to improve efficiency and price.

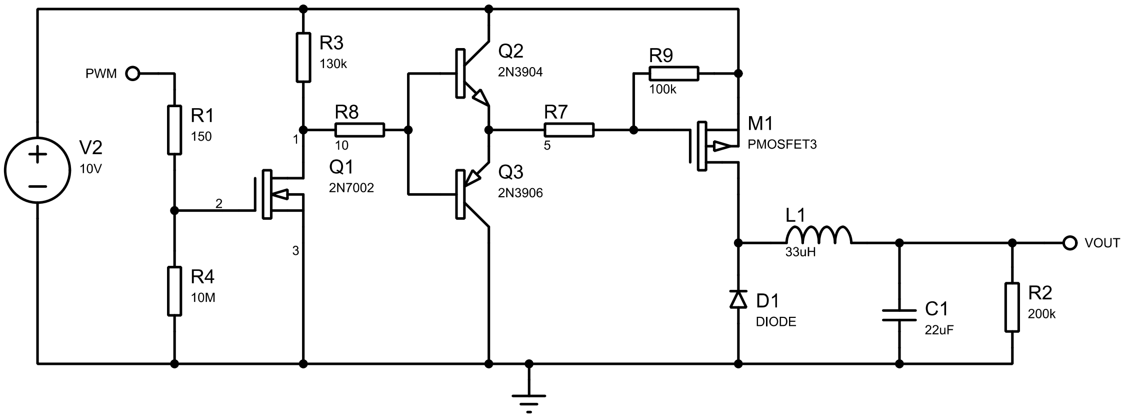

Fig. 7 Discrete buck converter with gate driver

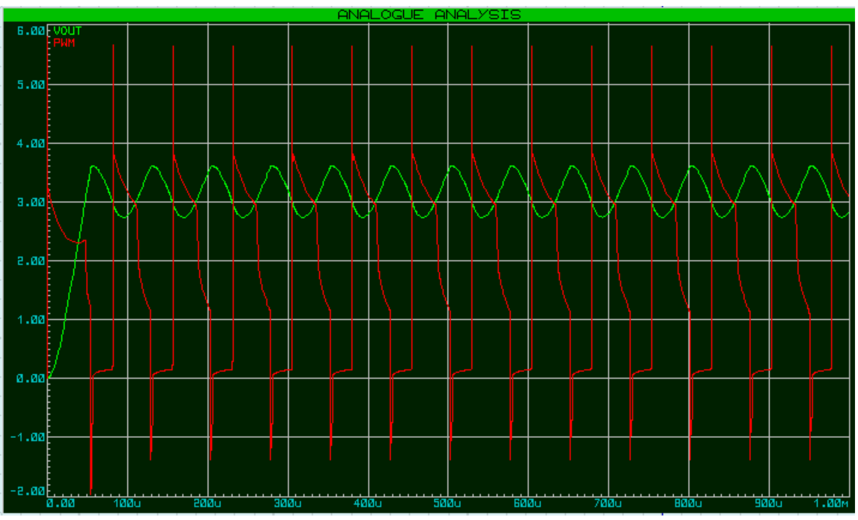

Fig. 8 Simulation

V. Experimental Results

The purpose of this measurement was check real efficiency, especially at very light loads. The first part of the measurements were done on four composed evaluation boards with LDO regulators and one with buck converter based on TPS62745 which was specially selected for this task. The second part will be focused to discrete solutions and their comparison. Measurement equipment was composed of standard laboratory devices. All measurements were done at room temperature with the same condition.

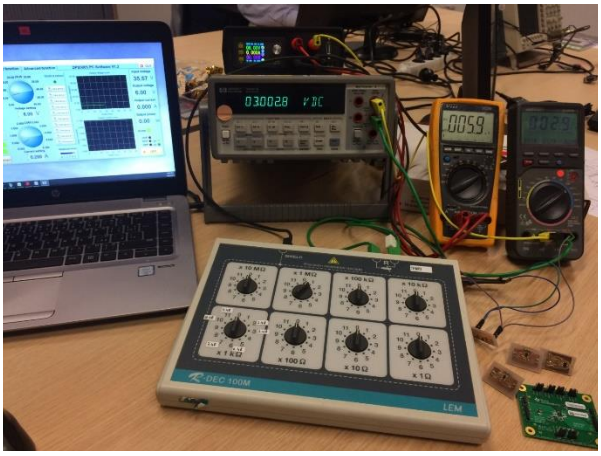

Fig. 9 Experimental measurement setup

The list of used components are shown in Table 3.

Table 3. List of used components

	Type	S/N
Programmable power supply	DP50V5A	PS1
Load	R-DEC 100M	P361628BA
Voltmeter	HP 34401A	488266
Voltmeter	HP 34401A	488266
Ammeter for input current	Vici VC99	2258016
Ammeter for output current	Voltcraft M-3860M	IJ096859
Proposed board 1	TPS62745EVM-622	430720028
Proposed board 2	HT7130	1
Proposed board 3	NCP551	1
Proposed board 4	XC6201	1
Proposed board 5	LP2982	1

Proposed boards can be seen in figure (Fig. 10).

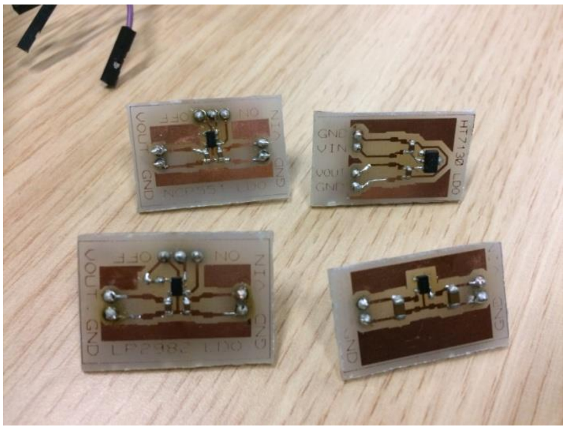

Fig. 10 Proposed board with LDOs

The results of the first part were like in the graph which is shown in figure (Fig 11). There is also no large difference between LDOs however, it is clearly visible that TPS based solution is much better even in light loads.

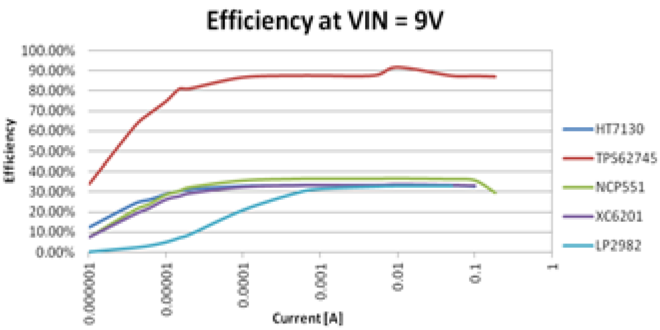

Fig. 11 Chart of experimental results

VI. Conclusion

Theory of DCDC converters especially buck converters are really enormous. There are a lot of things which needs to be considered during development. The paper provides results where commerce solution of switching DC/DC converter for such current consumptions are better choice.

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