Design Consideration for Low-Power Step-Up Converter

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***Abstract*— This paper describes the comparison of different MOSFETs and transformers used in a step-up circuit under initial voltages of 50 mV and 100 mV. Two MOSFETs, BSP149 and CPC3701CTR, and two transformers, CST-100LC and MID-SNS CS, were cross-connected, and the results of charging a 2200 µF capacitor were shown. This circuit consists of a Meissner oscillator and a voltage doubler circuit. Experimentally, the time it takes for different MOSFETs and transformers to increase the voltage and charge the capacitor at the circuit's output was measured, as well as the maximum output voltage generated by the circuit, and the resonant frequency for each of the given pairs of MOS transistors and transformers.**

***Index Terms*—step-up converter, transformers, MOSFET, power management.**

I. Introduction

In recent years, the WSNs technology create more interest in researching from macro to micro-level to develop systems without using conventional power supplies and exploring alternative power sources for WSNs (Wireless Sensor Nodes). Energy harvesting is a viable option for replacing low-power devices batteries or power supply. Energy harvesting necessitates the collaboration of three distinct technologies. For developing systems based on energy harvesting, there must be three separate technologies combined in working together: energy harvesters - used to convert ambient energy into electrical energy, power management - for amplifying and regulating the generated energy and energy storage - for powering low power consumption systems, such as sensors, actuators, microcontrollers, RF transceivers, etc. [1].

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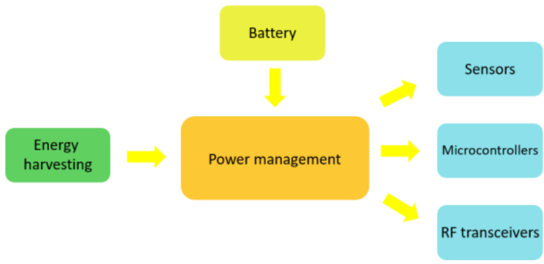

Fig. 1. Block scheme of energy harvesting system.

The block diagram of this kind of system is shown in Fig. 1. Low voltage and ultra-low power circuit design have become increasingly important recently. Low-power systems, such as those used in energy harvesting systems, wearable electronic devices, autonomous sensor nodes powered by non-conventional energy sources, the Internet of Things, and other similar applications, may require even lower supply voltage [2].

II. Voltage step-up circuit and experimental setup

A. Voltage step-up circuit

For the supply of an embedded system, it is required to employ an electrical boost converter to boost the harvested voltage to a voltage of higher values. When used in combination with energy harvesting, a step-up converter should be self-starting from as low as feasible input voltages without the usage of additional power. A low-voltage start circuit with an oscillator followed by a voltage multiplier is used to meet these design constraints. The electric circuit of a step-up circuit is shown in Fig 2.

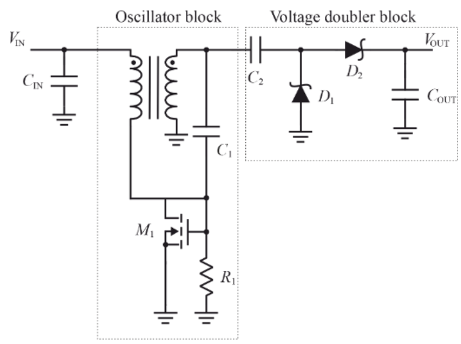

Fig. 2. Electric circuit of a voltage booster without energy harvesting block

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The minimal input voltage may be amplified significantly by changing the input DC energy into an AC form via an oscillator, then converting it back to DC with a boosted level by a voltage multiplier [3]. The oscillator block in this paper consists of a Meissner oscillator. It is needed to have an appropriate step-up ratio and have an adequate power conversion efficiency also.

At low input voltages, with the appropriate selection of MOS transistors and transformers, the Meissner oscillator begins to oscillate. If the input voltage is high enough, it undergoes a transition from its linear into a non-linear operation regime. The Meissner oscillator serves as a start-up circuit providing the supply voltage for a separate, inductor-based step-up converter from an input voltage of 50 mV and 100 mV for this experiment, followed by a voltage doubler circuit. When comparing different step-up converters, the parameters of start-up voltage and self-supply, as well as the employed circuit idea, are key factors to take into account. Low-voltage step-up converters are a popular subject of research, and of course, there are commercially produced devices. These converters have start-up voltages as low as 20 mV in some cases [4]. The capacitor C_2, which is part of the voltage doubler circuit, influences the maximum output current value. When utilizing a transformer with a ratio of 1:100 and working from very low input voltages, a minimum value of 1 nF is advised [4]. When operating at low input voltage or with high resistance sources, a large capacitor value may affect circuit performance. In this circuit, the gate coupling capacitor C_1 is employed. When the input voltage surpasses 50 mV, the capacitor's voltage value capacitor is increased to the point where oscillations occur rapidly. The experimentally established value for capacitor C_1 is 4.7 nF. Because of resistor R_1, the circuit's oscillations start consistently. The resistor R_1 of 2.2 MΩ is the predefined value. Schottky diodes are being used in this circuit for the voltage doubler (D_1 and D_2). The selected diodes have better frequency response and lower forward voltage than standard Si diode due to the lower forward voltage, and that is the reason for their implementation in this circuit. The energy is stored in the electrolytic capacitor C_{OUT}, which has a capacitance of 2200 μF. The choice of transformer is crucial in the circuit design process, and it will be considered in the experimental setup. High quality factor Q, compact footprint area, and high turns ratio are the main characteristics of the transformer for low voltage step-up oscillators. The step-up oscillator is coupled to the voltage source that drives the current through the primary trnasformer winding L_1 and the depletion-mode MOSFET. This current causes a positive voltage to be induced on the secondary transformer winding L_2, which raises the gate voltage of transistor M_1 and hence the primary winding current. The secondary winding voltage begins to diminish when this current reaches core saturation. The transistor begins to switch off the current via the transformer's main winding, resulting in a voltage reversal at the secondary winding and a negative gate voltage. The transistor is promptly turned on and remains active until the primary winding current reaches saturation, at which point the oscillation process restarts. The signal from the step-up oscillator is received by a half wave voltage doubler (V_{OSC}). In the voltage doubler circuit, capacitor C_2 and diode D_1 create a clamp, while the diode D_2 and capacitor C_{OUT} create a peak rectifier. Diode D_1 conducts during the negative half cycle of an input voltage signal, charging capacitor C_2 to the voltage $V_{C2}= V_{D1}-V_{OSC}$. Diode D_1 is turned off during the positive half cycle of the input signal, while diode D_2 conducts charging capacitor C_{OUT} [5]. The output voltage will be:

$$V_{\mathrm{OUT}} = V_{\mathrm{OSC}} - V_{\mathrm{C2}} - V_{\mathrm{D2}} = 2(V_{\mathrm{OSC}} - V_{\mathrm{D}}) \tag{1}$$

B. Experimental setup

The major purpose of this study is to see how different pairings of transformers and transistors affect the generation of output voltage in the stated circuit, depending on whether a 50 mV or 100 mV voltage is provided to the circuit's input. The BSP149 and CPC3701CTR NMOS depletion mode transistors were used for the experiment. Since of its negative threshold voltage (V_{th}), the depletion mode n-type MOSFET BSP149 (M_1) was chosen because it is in a normally-on state at low voltages [6]. The transistor's low drain-source on-state resistance, which ranges from 1.7 Ω to 3.5 Ω, is the transistor's second advantage.

The CPC3701CTR transistor has lower drain-source on-state resistance of 1 Ω than transistor BSP149 [7]. The drain-source on-state resistance is an important characteristic of the depletion mode n-type MOSFET for the reason that this resistance affects power loss, and can be calculated as:

$$R_{\mathrm{DS(ON)}} = \frac{1}{\mu_{\mathrm{n}} \cdot C_{\mathrm{OX}} \frac{W}{L} (V_{\mathrm{GS}} - V_{\mathrm{th}})} \tag{2}$$

where is μ_n – carrier mobility, C_{OX} – oxide capacitance, W – channel width, L – channel length, V_{GS} – gate-source voltage, and V_{th} – threshold voltage.

As previously noted in the paper, the micro transformer with a ratio of 1:100 was chosen. For this experiment, transformers from different manufacturers were taken, but with similar characteristics and the same transformation ratio. The first transformer is CST-100LC, which has an inductance of 2 mH and a resistance of 5 Ω [8], while the second is a MID-SNS-CS with an inductance of 5.6 mH and a resistance of 0.85 Ω [9].

Since it is necessary to use a pair of transistor and transformer in the circuit, based on an input voltage of 50 mV in the first case and 100 mV in the second, it was decided to test all possible transistor and transformer combinations and then compare the output values of various parameters. These combinations are BSP149 MOSFET and CST-100LC transformer, BSP149 MOSFET and MID-SNS CS transformer, CPC3701CTR MOSFET and CS-100LC transformer, and CPC3701CTR MOSFET and MID-SNS CS transformer.

The expected results are that the MOS transistor CPC3701CTR in combination with some of the transformers can generate the highest output voltage since it has better characteristics than the BSP149 transistor, specified in the datasheet.

III. Results and Discussion

The input voltage V_{IN} simulates the generated voltage given by one of the energy harvesting block. In this case, DC voltage input is generated by a voltage supply at 50 mV and 100 mV instead of an energy harvesting voltage source. Fig. 3 shows the time that elapsed until the voltage on the capacitor reached 3.3 V and 5 V. The result of this measurement shows that the CPC3701CTR MOSFET and CST-100LC transformer take the longest time to generate specified output voltages. The shortest time to generate these values of voltage is measured for CPC3701CTR MOSFET and MID-SNS CS transformer, which indicates that they are the most efficient MOSFET-transformer pair in this research.

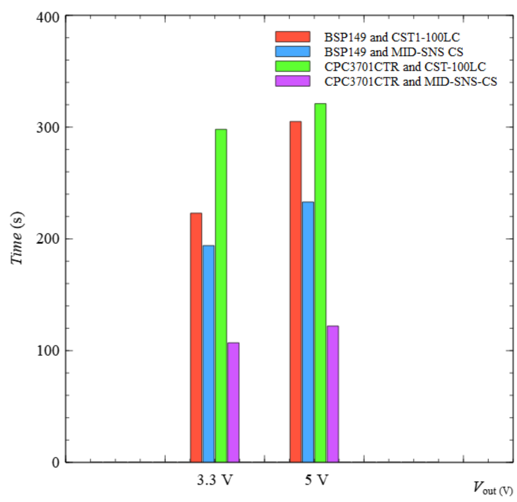

Fig. 3 Measured time for generating 3.3 V and 5 V on the output capacitor C_{OUT} (2200 µF) for different pairs of transformers and MOS transistors.

Fig. 4 shows the maximum output voltage at the capacitor C_{OUT} when the circuit reaches a steady-state and the given results are for 50 mV and 100 mV of the input voltage.

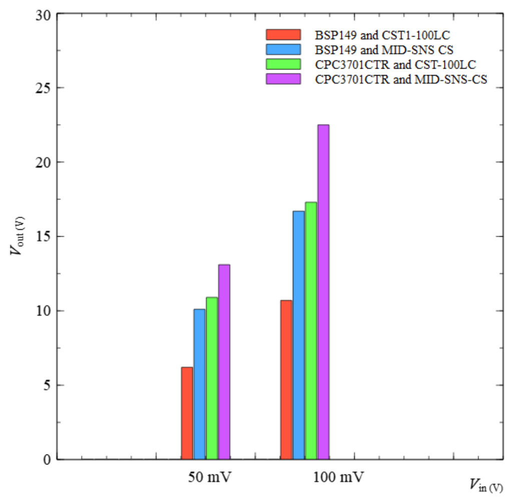

Fig. 4 Maximum generated output voltage on the capacitor C_{OUT} for different pairs of transformers and MOS transistors at the input voltages of 50 mV and 100 mV.

It is measured that CPC3701CTR along with MID-SNS CS transformer can generate the biggest output voltage at the capacitor C_{OUT}, and the lowest produced voltage in these combinations of MOSFETs and transformers is for BSP149 MOSFET in pair with CST-100LC transformer. For the stated measurements, the best performances of the MOSFET-transformer pair are for the CPC3701CTR MOSFET and MID-SNS CS transformer, as expected. The resonate frequency of each MOSFET-transformer pair is presented in Fig 5. The highest resonating frequency is measured for CPC3701 MOSFET and CST-100LC transformer, and the lowest resonating frequency is measured for BSP149 MOSFET with MID-SNS CS transformer. Fig. 6 – Fig. 9 represent the output voltage generation for all of the measured MOSFET-transformer pairs, at the initial voltage of 100 mV, captured by the Tektronix DPO4034 oscilloscope.

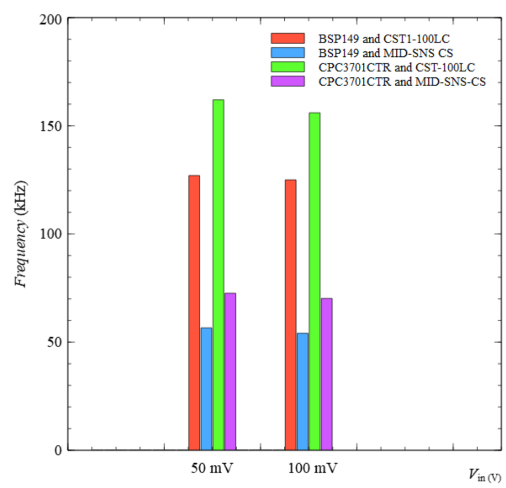

Fig. 5 Measured resonant freaquency for generating 3.3 V and 5 V on the output capacitor (2200 µF) for different pairs of transformers and MOS transistors.

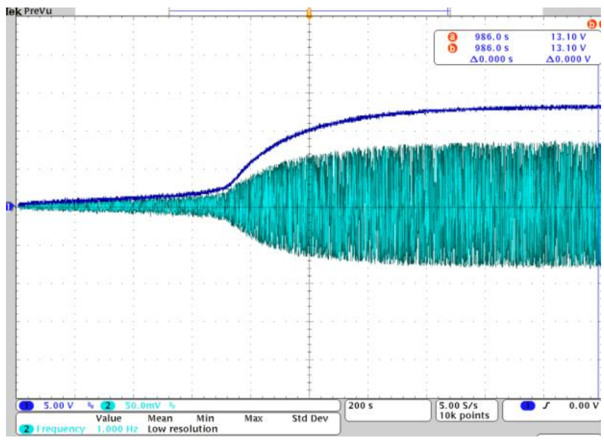

Fig. 6 BSP149 MOSFET and CST-100LC transformer pair: The oscillator voltage (light blue) and the voltage at the output capacitor C_{OUT} (deep blue) as a function of time for the initial voltage of 100 mV. X-axis: 200 s/div, Y-axis: 5 V/div for V_{OUT} and 50 mV for V_{OSC}.

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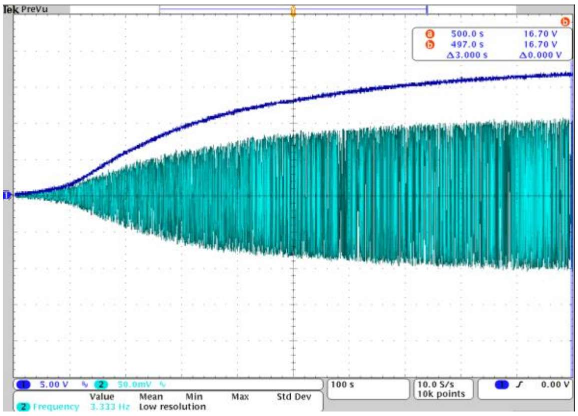

Fig. 7 BSP149 MOSFET and MID-SNS CS transformer pair: The oscillator voltage (light blue) and the voltage at the output capacitor C_{OUT} (deep blue) as a function of time for the initial voltage of 100 mV. X-axis: 100 s/div, Y-axis: 5 V/div for V_{OUT} and 50 mV for V_{OSC}.

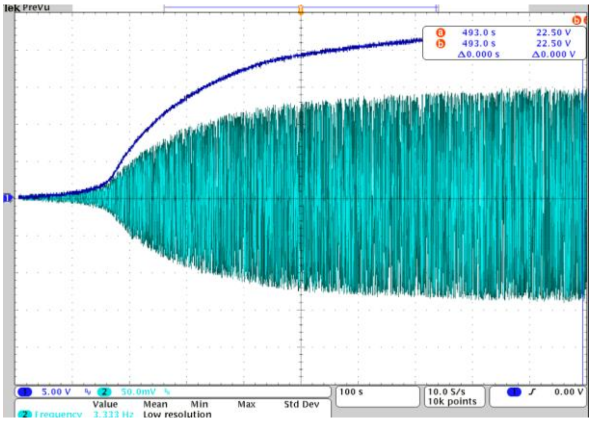

Fig. 8 CPC3701CTR MOSFET and CST-100LC transformer pair: The oscillator voltage (light blue) and the voltage at the output capacitor C_{OUT} (deep blue) as a function of time for the initial voltage of 100 mV. X-axis: 100 s/div, Y-axis: 5 V/div for V_{OUT} and 50 mV for V_{OSC}.

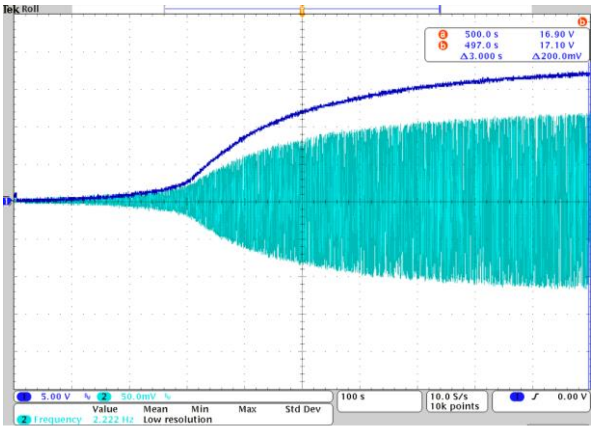

Fig. 9 CPC3701CTR MOSFET and MID-SNS CS transformer pair: The oscillator voltage (light blue) and the voltage at the output capacitor C_{OUT} (deep blue) as a function of time for the initial voltage of 100 mV. X-axis: 100 s/div, Y-axis: 5 V/div for V_{OUT} and 50 mV for V_{OSC}.

IV. Conclusion

It is a great challenge to choose the components that will provide the highest efficiency of the power management circuit, but it is one that must be addressed depending on the purpose of the circuit behind the power management block. Depending on that, it is necessary to pay attention to how the components affect the power loss, which ones generate the highest output voltage, which ones reach a certain value of the output voltage for the shortest time, etc. This paper shows how different transformers and MOS transistors affect all of the parameters stated above, and it is possible to choose a pair depending on the needs of the circuit powered by such a system. In terms of generating the highest possible output voltage on the C_{OUT} capacitor it is best to use a CPC3701CTR MOSFET with a MID-SNS CS transformer, for a lower input voltage at 50 mV but at 100 mV as well. If the user needs a power management circuit that generates an output voltage in the shortest time, the best option is a pair of CPC3701CTR MOSFET and a MID-SNS CS transformer. The pair of a CPC3701CTR MOSFET and CST-100LC transformer is the second-best for generating maximum output voltage, but it needs the longest time to generate the desired voltage. In the future, this type of step-up converter will be improved by adding and testing additional components to the circuit in order to give the shortest time for the oscillation process.

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