MODELING AND SIMULATION OF PIEZOELECTRIC ENERGY HARVESTING POWER SUPPLY CHIP

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Резюме. В статията са представени предварителните резултати от изследването, анализа, моделирането и симулацията на интегралната схема за захранване от околната среда LTC 3588 на Linear Technology. Разработен е Simulink модел от високо ниво, основаващ се на функционален анализ на пиезоелектрическия преобразувател и на известното от литературата математическо описание на понижаващия преобразувател. Моделът ще се използва за предвиждане на поведението на пиезоелектрични устройства за захранване от околната среда. Той е изследван за типичните приложения на интегралната схема. Получените резултати потвърждават избрания подход.

Ключови думи: Energy harvesting, High-level modeling, Simulink

INTRODUCTION

Computer simulations are an integral part of the entire contemporary design process in electronics. They are utilized to predict the behavior of a system that is to be developed. To achieve this, a high-level model of the real system is created.

Energy harvesting is a new tendency in the development of the "green technologies". Linear's Technology LTC 3588-1 chip integrates all necessary blocks for implementation of piezoelectric energy harvesting devices (see Figure 1) [1].

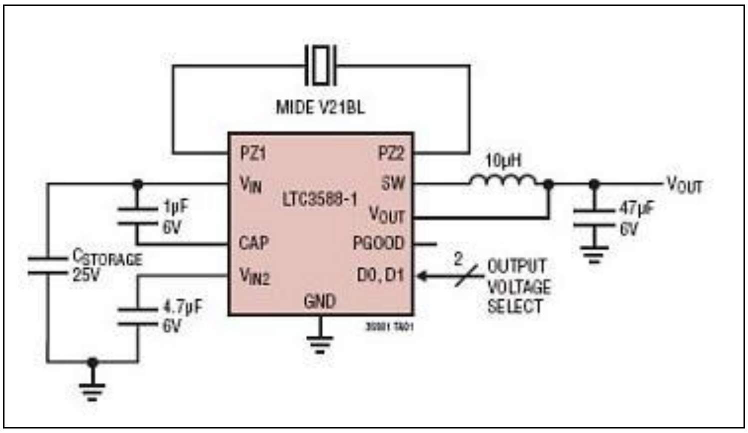

Figure 1. Application of LTC 3588-1 chip as 100mA energy harvesting power supply [1].

This paper presents the preliminary results from investigation, modeling and simulation of the piezoelectric energy harvesting power supply chip LTC 3588 of Linear Technology. To this aim a Simulink model, based on the functional analysis of the piezoelectric transducer and the known mathematical description of the buck converter, is developed. The model is verified for a typical application of the chip. The obtained results confirm usefulness of the applied approach.

PIEZOELECTRIC ENERGY HARVESTERING POWER SUPLLY CHIP

Linear Technology LTC 3588 chip [1]

Figure 2 presents the internal structure of LTC3588-1. The AC piezoelectric signal is rectified by an inbuilt full-wave bridge rectifier. Under voltage lockout (UVLO) block enables operation of buck converter in presence of enough power to be transferred from input to the output. When the voltage level on the input capacitor is below the UVLO failing threshold, the buck converter is disabled. The buck converter is formed by switches, a control block and an external inductor and capacitor. The control block drives one PMOS and one NMOS transistor on/off. Buck converter uses hysteretic voltage algorithm to control the output trough internal feedback from Vout pin. If the converter delivers output voltage in regulation, it settles in low quiescent current sleep state and monitors output trough a voltage comparator. The presence of regulated output voltage is indicated by the power good comparator. It monitors the Vout pin and produces logic high on PGOOD pin when it is in regulation.

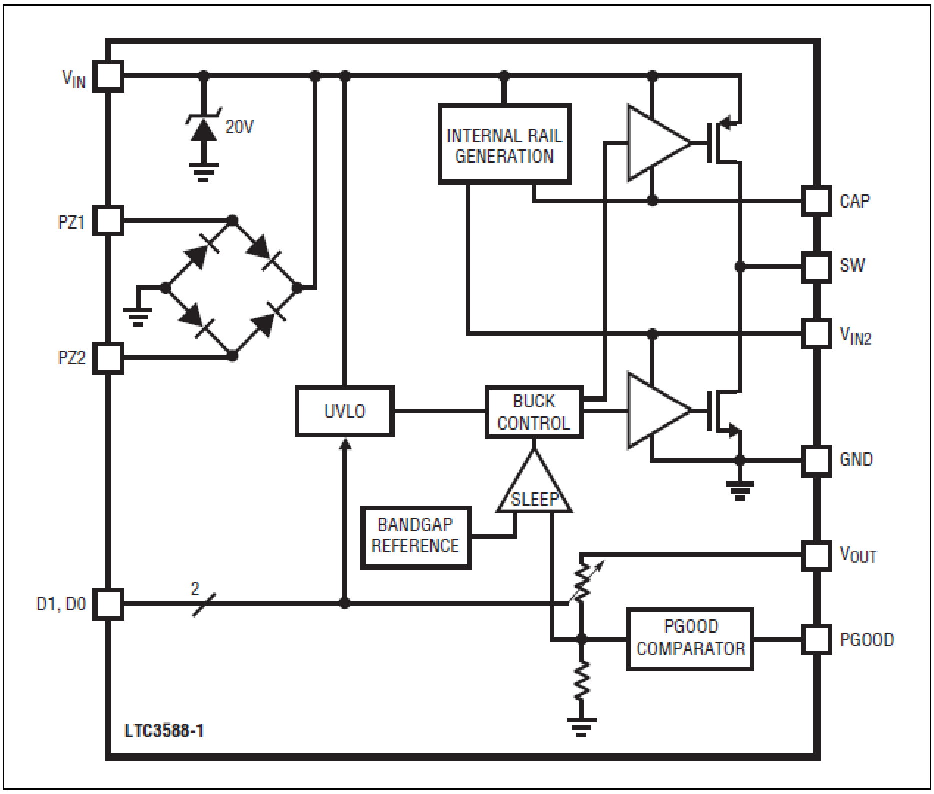

Figure 2. Block diagram Linear Technology LTC 3588

High-level (Major or General) model

Figure 3 depicts the highest-level block diagram of the proposed Simulink model. The piezoelectric cantilever beam block models the behavior of the piezoelectric cantilever beam and the full-wave bridge rectifier followed by a capacitor. The generated output waveform *PZ* is connected to the input *VIN* of the buck converter model for further processing. The buck converter block comprises two input ports – *VIN*, *SW* and three output ports – *VOUT*, *IL* and *VC*. The *VIN* - input voltage of the buck converter block is connected to the output waveform for piezoelectric cantilever beam (PCBB) block. The *SW* signal defines the switching frequency and duty cycle of the converter. *VOUT* is the output voltage for the buck converter, *IL* is the current trough the inductor and *VC* is the signal for the voltage level on the output capacitor.

The V^2 *CONTROL* block produces a control pulse-width modulated signal with correlation of the voltage levels *VOUT*, *REF* and load changing conditions. The *PGOOD* block monitors the output voltage and compares it to the reference voltage level. In case of *VOUT>REF* it delivers a high logic level on the *PGOOD* output.

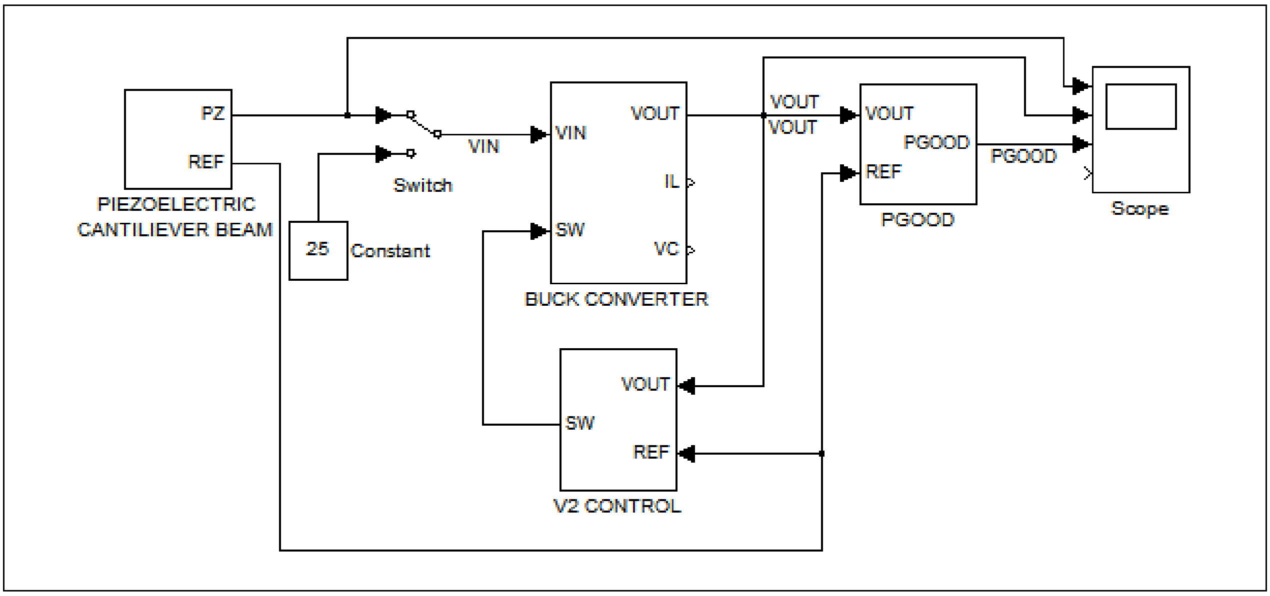

Figure 3. General block diagram of Simulink model

Piezoelectric cantilever beam block (PCBB)

Figure 4 shows the piezoelectric cantilever beam block which consists of a voltage source of sinusoidal signal $\boldsymbol{F(t)}$ produced under sinusoidal harmonic excitation, a full-wave bridge rectifier and a capacitor as energy reservoir[2].

$$F(t) = F_0 \sin \omega t, \quad (1)$$

where $\boldsymbol{F_0}$ = 24V is the constant magnitude and ω = 257.6rad/s is the angular frequency.

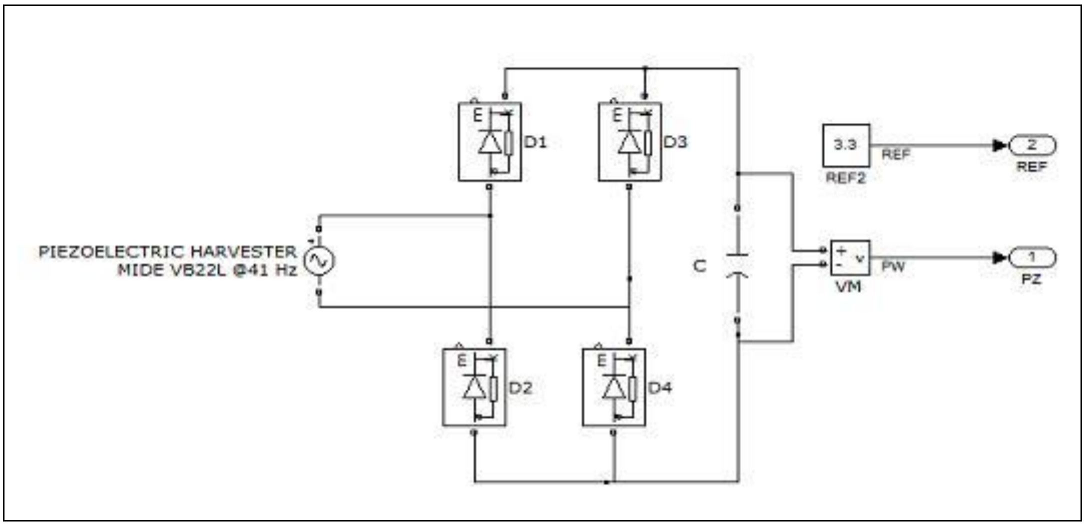

Figure 4. Piezoelectric cantilever beam block

Buck converter

A small signal low-frequency model of a switching dc-to-dc converter working in the continuous conduction mode is proposed in [3]. The parasitic effects (such as switch conduction voltages, conduction resistances and ESR's of capacitors) are accounted in the state-space model described by equations (2) and (3) [4].

$$\begin{bmatrix}\frac{di_L(t)}{dt}\\ \frac{dv_C(t)}{dt}\end{bmatrix} = \begin{bmatrix}\frac{-(R_{on}+R_L+(R||R_C))}{L} & -\frac{R}{L.(R+R_C)}\\ \frac{R}{C.(R+R_C)} & -\frac{1}{C.R+R_C}\end{bmatrix}\begin{bmatrix}i_L(t)\\ v_c(t)\end{bmatrix} + \begin{bmatrix}SW\\ 0\end{bmatrix} v_s(t), \quad (2)$$

$$\begin{bmatrix}v_O(t)\\ i_S(t)\end{bmatrix} = \begin{bmatrix}(R||R_C) & \frac{R}{R+R_C}\\ 0 & 0\end{bmatrix}\begin{bmatrix}i_L(t)\\ v_0(t)\end{bmatrix}, \quad (3)$$

where i_L – denotes inductor current, v_O –output voltage, v_C – capacitor voltage, v_S – source voltage, SW – duty cycle, R_{on} = 1Ω – on-state switch resistance, L= 22µH – inductance, R_L = 0.5Ω, C =10µF – capacitor, R_C =0.5Ω – capacitor ESR, R = 33 and 500kΩ load resistance.

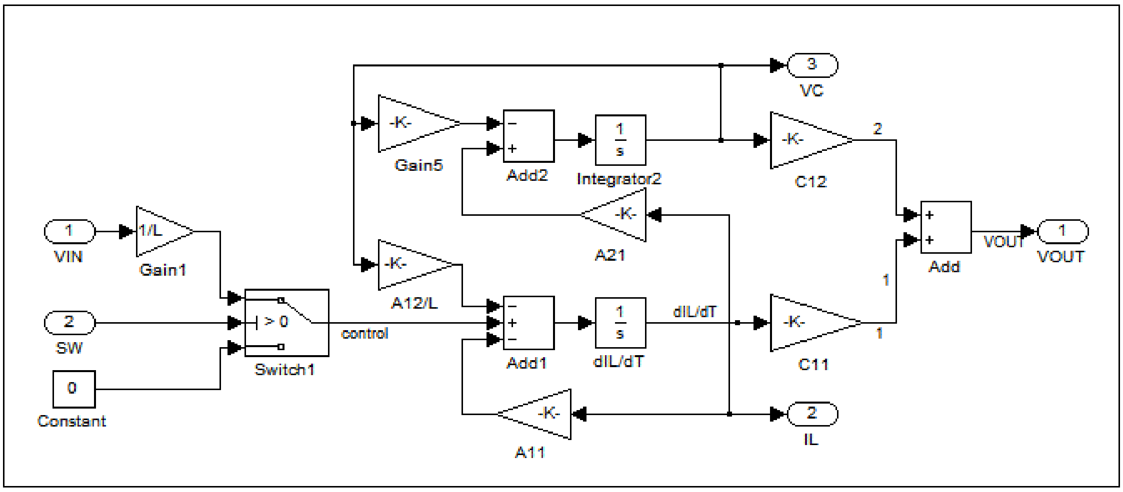

Figure 5. Simulink implementation of state-space buck converter model

Figure 5 displays the Simulink implementation of the state-space buck converter model (equations (2) and (3)) with included parasitic effects. The block has two input ports: *VIN* – input voltage from the energy harvester block and *SW* – duty cycle for the switching element. The output ports are: *VOUT* – output voltage, *IL* – inductor current, *VC* – capacitor voltage level.

V^2 control block

The energy harvesting power supply should be able to power microcontroller and radio transmission circuits. Usually they are working within 3% duty cycle [5], and need a high-current slew rate. As a result, the power supply should possess a fast transient response. This requires the energy harvesting power supply to use a feedback control mode algorithm. Three common types of controlling algorithms are used in practice: voltage mode control, current mode control and V^2 mode control. Using output ripple for a source to the ramp signal, buck converters that are controlled by the V^2 control mode have the fastest transient response to load variations and changing input voltage [6]. Due to this reason V^2 mode control is applied in the presented model.

V^2 consists of an error amplifier and PWM comparator. Model implementation is shown on Figures 6a and 6b. The comparator has two inputs: *VOUT*- output voltage, *VERR* - output error from error amplifier. Output is *SW* – duty cycle for a switching element. A set-reset flip-flop is used to generate controlling signals. Figure 6b displays the implementation of the error amplifier. Input ports are *VREFF* – reference voltage and *VOUT* – output voltage from converter. Output port is *VERR* – error current. The used transconductance is 6mS, output impedance – 4MΩ and compensation capacitor – 1μF.

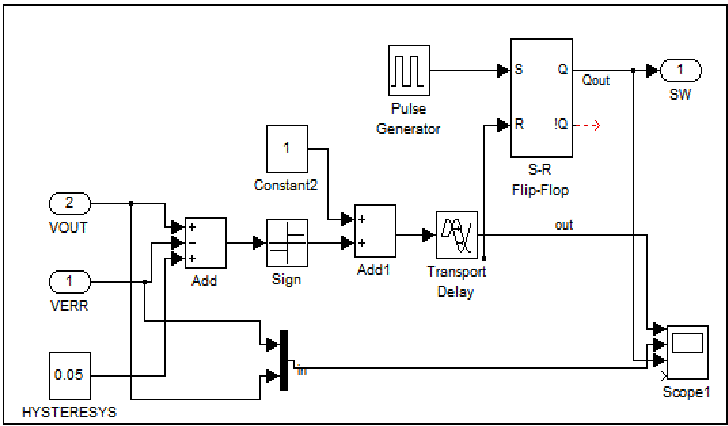

Figure 6a. PWM Comparator

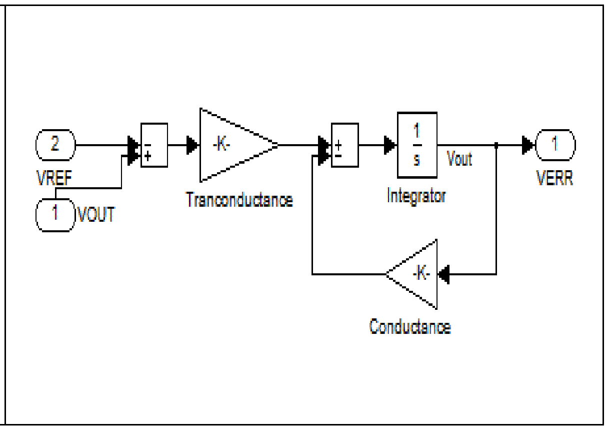

Figure 6b. Error Amplifier

SIMULATION RESULTS

Figure 7 depicts the simulation results. The continuous line denotes the output voltage *VOUT*, the dashed lines is the output voltage from the piezoelectric cantilever beam *Vpz* and the dotted line is the *PGOOD* voltage. This result is obtained with R = 500kΩ and is very close to what is presented in the datasheets.

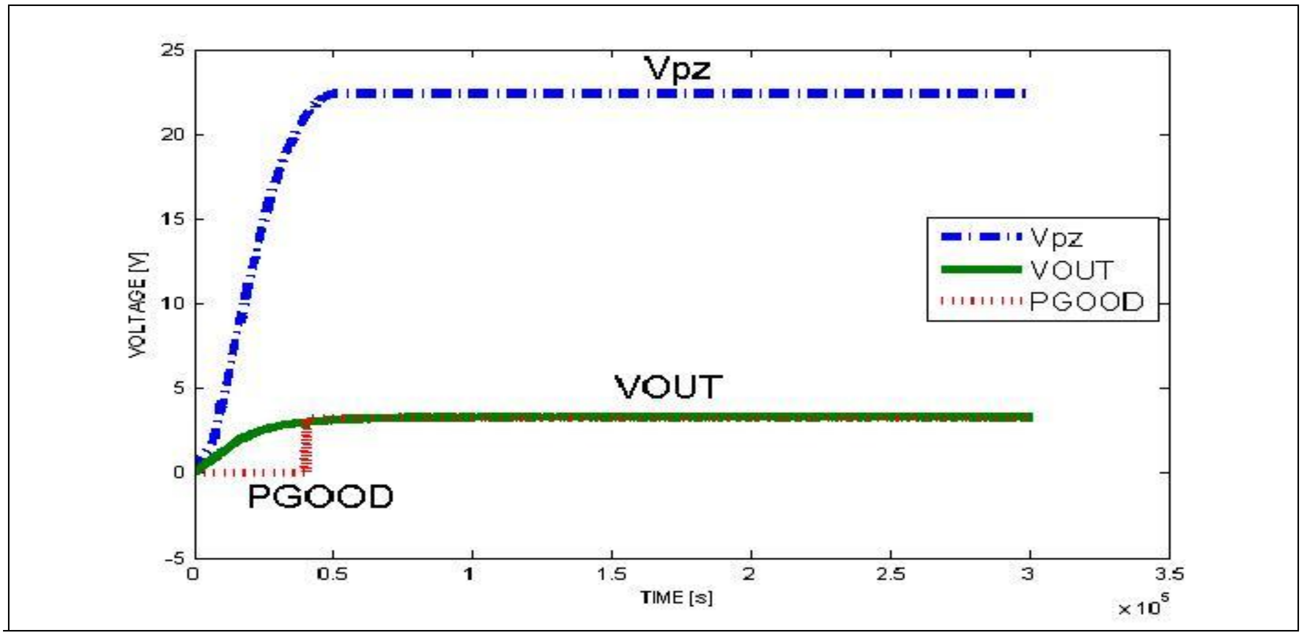

Figure 7. Simulation results

CONCLUSIONS

The paper presents a Simulink model of a piezoelectric energy harvesting power supply chip. To this aim a general block diagram of a Simulink model is described and the structures of the different blocks are developed. The simulation results are very close to the reality and this encourages us to continue to work in this direction. Further work will involve the under voltage lockout block, modeling of energy transfer from the energy harvester to the output capacitor and modeling of the piezoelectric cantilever beam with correlation between geometric properties and generated output voltage.

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