Hysteresis controlled MPPT for piezoelectric energy harvesting

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Abstract A hysteresis controlled MPPT method is proposed to improve the efficiency of piezoelectric energy harvesting (PEH). According to the characteristics of the PZH output power, the maximum output power can be obtained when the piezoelectric transducer (PZT) output voltage is controlled nearby the 1/2 open-circuit voltage (optimal output voltage). A hysteresis window for maximum power point controlled is implementing with the energy storage circuits, which optimize the voltage of PZT output after rectification to optimal output voltage. Experimental results show that the MPPT control method with the hysteresis window can effectively track the optimal output voltage. The maximum power tracking efficiency \( \eta_{\text{MPPT}} \) is high to 98.7% with the variety of the ambient vibration energy.

Key words: MPPT, energy storage, piezoelectric energy harvesting

Classification: Energy harvesting devices, circuits and modules

1. Introduction

Wireless Sensor Networks (WSNs) technology has been deeply involved in all aspects of people's lives, such as biological medical equipment, automobile tire pressure monitoring, environmental monitoring, rescue and disaster relief and other applications. Most WSN nodes are powered by batteries at present. However, with the development of WSNs, the batteries for WSN nodes have been in face with serious challenges, especially in the life of the batteries. Therefore, researchers are eager to find durable and reliable ways to power the WSN nodes. Energy Harvesting, which collects different forms of ambient energy to power the WSN nodes, has become a frontier technology area of the academia and the industry [1,2]. Typical ambient energy such as the vibration energy, solar energy, wind energy and heat energy are all catching the sight of the researchers. However, the piezoelectric energy harvesting (PEH) system with the advantages of high energy density and easy integration has become a research focus [3,4,5].

As the piezoelectric transducer (PZT) has a high impedance with small current, high voltage AC output, which cannot directly power the WSN nodes. It is necessary to convert the AC output into DC (ac-dc conversion) [6,7,8,9,10]. Therefore, in order to improve the energy conversion and utilization, plenty of methods, like high efficient piezoelectric transducers, low power full bridge rectifiers or active rectifiers, DC-DC converters or charge pumps and other essential modules have been studied and reported in the past decades [11,12,13,14]. Various interface circuits, including parallel synchronized switch harvesting on inductor, synchronous electronic charge extraction or standard module have also been developed [15,16,17,18]. Moreover, the output characteristics of PZT varies with environmental conditions, which significantly affects the energy harvesting efficiency. Hence, the maximum power point tracking (MPPT) technology was proposed [19,20,21,22]. Traditional MPPT technology requires an external MCU to track the MPP by frequently detecting the PZT output voltage or current or both. However, the MCU consumes significant power and may not be efficient in micropower ambient energy situations [23,24,25,26,27,28]. Ge Shi et al [29] proposed a power management circuit based on quasi-maximum power point tracking. A bidirectional Buck-Boost DC-DC converter was designed to quickly regulate the filter capacitor voltage, which got a fast tracking of maximum power. However, the structure is complicated and the power consumption is a bit high for weak energy harvesting systems.

In this paper, a hysteresis controlled MPPT method with energy storage circuit is proposed to track the maximum power point of the PZT output and increase the efficiency of the energy harvesting [30].

2. Design of the proposed hysteresis controlled MPPT

The PEH system with the proposed hysteresis controlled MPPT is shown in Fig. 1.
Voltage drop, $D = V_{CS}$, 

$V_{CC} - V_{CS} = D_{1}V_{S}$ 

Stage: M1 is turned on and M4, M5 are turned off when $V_{C}$ is reduced to $V_{CS} + |V_{THP}|$, which causes an instantaneous current rushing from C1 to Ct. $V_{C}$ drops rapidly until it is equal to $V_{CS}$, and then $V_{C}$ reaches its minimum, and the circuit enters Stage 1 again. Since Stage 3 is a short transient process, the effect of the PZT current can be ignored.

Stage 3: M2, M3 are turned on and M4, M5 are turned off when $V_{C}$ decreases to $V_{CS} + |V_{THP}|$, which causes an instantaneous current rushing from C1 to Ct. $V_{C}$ drops rapidly until it is equal to $V_{CS}$, and then $V_{C}$ reaches its minimum, and the circuit enters Stage 1 again. Since Stage 3 is a short transient process, the effect of the PZT current can be ignored.

Stage1: $V_{C} < V_{CS} + |V_{THP}|$ ($V_{THP}$ is the threshold voltage of PMOS), M1 is turned off, and $V_{R}$ is “0”, which makes $ctr1 = 0$ and $ctr2 = 1$ to turn on M2, M3 and turn off M4, M5. Therefore, a part of the current flows into the DC-DC converter to power the load. The diode D5 is designed to prevent current from flowing back causing energy loss. And another part of the current charges the capacitors C1 and Ct to increase the voltage of $V_{C}$ and $V_{CS}$, which are approximately equal, since M2 and M3 has a low forward voltage drop. When $V_{C}$ is increased to $V_{CS} + |V_{THP}|$, the circuit will work in Stage 2.

Stage 2: While the voltage $V_{C}$ increases to $V_{CS} + |V_{THP}|$, M1 is on, so $V_{R}$ becomes “1”, $ctr1$ turns M2, M3 off and $ctr2$ turns M4, M5 on. Therefore, Ct is connected with Cs but not C1, and the current flowing through M4, M5 to discharge Ct to Cs. With the discharge of Ct, $V_{C}$ is reduced until under $V_{CS} + |V_{THP}|$, $V_{C}$ is approximately equal to $V_{R}$. Then the circuit will come into Stage 3. During this period, the PZT continues to power the DC-DC converter, and $V_{C}$ continues to rise and incremented by $\Delta V$. $V_{C(max)}$ can be expressed as:

$$V_{C(max)} = V_{CS} + |V_{THP}| + \Delta V$$ (1)

Based on the above analysis, the relationships between variables are as follows:

$$V_{C(max)} - V_{C(min)} = \frac{Q_{C}}{C_{1}} - \frac{Q_{C}}{C_{1}} - \Delta Q_{C}$$

$$\Delta Q_{C} = C_{1} \Delta V_{C} = \frac{C_{1}}{C_{1}} \left( V_{C(max)} - V_{C} \right)$$

$$\Delta V = \frac{(C_{1} + C_{C}) (V_{C(max)} - V_{C(min)} - \Delta V)}{T_{1}} T_{2} \frac{T_{2}}{C_{1}}$$ (3)

$T_1$ and $T_2$ are the time of Stage 1 and Stage 2,
respectively.

According to Eq. (1), (2) and (3),

$$V_{C\text{(max)}} = \frac{V_{c0} + |V_{\text{ThP}}| - kV_S}{1-k}$$

(4)

In which, $k = C_f / C_1 \left[ 1 + \frac{T_1 C_f}{T_2(C_f + C_t)} \right]$, and $0<k<1$.

$$V_{C\text{(min)}} = V_{C\text{(max)}} - \frac{C_f}{C_1} (V_{C\text{(max)}} - V_S)$$

(5)

And the average voltage of $V_C$ is:

$$V_{avg} = \frac{V_{C\text{(max)}} + V_{C\text{(min)}}}{2} = V_{C\text{(max)}} - \frac{C_f}{2C_1} V_{C\text{(max)}} + \frac{C_f}{2C_1} V_S$$

$$= (1 - \frac{C_f}{2C_1}) V_{c0} + |V_{\text{ThP}}| - kV_S + \frac{C_f}{2C_1} V_S$$

$$= \frac{2C_f - C_f}{2C_1} (V_{c0} + |V_{\text{ThP}}|) + \left( \frac{C_f}{2C_1} - \frac{2C_f - C_f}{2C_1} k \right) V_S$$

$$V_{avg}$$ is our real optimal tracking voltage. As $T_1 >> T_2$, $C_f >> C_t$, the coefficient of $(V_{c0} + |V_{\text{ThP}}|)$ is approximately equal to 1, and the coefficient of $V_S$ is near to 0. Since $V_{c0} + |V_{\text{ThP}}| = V_{oc}/2 - |V_d| + |V_{\text{ThP}}| = V_{oc}/2$, our real optimal tracking voltage $V_{avg}$ is very close to the ideal value $V_{oc}/2$, but has small variation with $V_S$.

In order to get a better tracking, the hysteresis window voltage $\Delta V_{hw}$ is designed to be tiny. Its expression is as follows:

$$\Delta V_{hw} = V_{C\text{(max)}} - V_{C\text{(min)}} = \frac{C_f}{C_1} V_{C\text{(max)}} - \frac{C_f}{C_1} V_S$$

(7)

Both $\Delta V_{hw}$ and $V_{avg}$ can be optimized by the ratio of $C_1$ to $C_t$. Cascaded switch-controlled capacitors can be used in energy storage circuit if necessary. Stages 1–3 work alternately over and over, until next sampling phase comes.

The experimental device is shown in Fig. 4, which is built up with a piezoelectric cantilever and the proposed MPPT circuit. The main mechanical structure is a copper cantilever in which one terminal is fixed by mounting bracket on the vibration shaker while the other one is free. A 60mmx30mm piezoelectric element is bonded on the cantilever. A mass is attached to the free end of the
cantilever to reduce the vibration frequency and increase the free end displacement.

Besides, a simple full bridge rectification circuit is built as a contrast [23]. The circuit is tested with different load resistors, and the maximum power of the PZT ($P_{\text{max}}$) is measured. $P_{\text{MPPT}}$ is the output power of the proposed circuit. The maximum power tracking efficiency $\eta_{\text{MPPT}}$ is given by Eq. (8).

$$\eta_{\text{MPPT}} = \frac{P_{\text{MPPT}}}{P_{\text{max}}}$$  \hspace{1cm} (8)

Fig. 5 shows the measured output power of the proposed circuit compared with the maximum output power of the contrast circuit and the maximum power tracking efficiency. The results shows that the tracking efficiency of the proposed MPPT circuit is above 95%, and up to 98.7%. Table II compares the performance of the proposed MPPT circuit with recently reported MPPT circuit for piezoelectric energy harvesting.

![Fig. 5. The measured results: Output power and tracking efficiency](image)

Table II. Comparison of PE energy harvesting systems

| Publication | TPEL 2012[25] | sensors 2014[7] | TPEL 2018[23] | TPEL 2019[30] | This work |
|-------------|---------------|----------------|---------------|---------------|-----------|
| MPPT algorithm | Resistor matching | Resistor matching | Fractional VOC | Fractional VOC | Fractional VOC |
| Input voltage | 3–25V | 1.62–7.04V | N/A | 3.54–25V | 5–12V |
| Frequency | 47HZ | 234.5HZ | 2–10HZ | 50HZ | 18HZ |
| Converter type | flyback | Buck-boost | buck | Buck-boost | buck |
| Energy storage unit | no | yes | no | yes | yes |
| Load power off | no | yes | yes | no | no |
| Maximum MPPT efficiency | 94% | N/A | 98.28% | 98.4% | 98.7% |

4. Conclusion

A hysteresis controlled MPPT method is presented in this paper. The hysteresis window controller with energy storage composed of some logical control blocks and several capacitors is used to keep the output voltage of the PZT in MPP adjacent area, which leads to a high maximum power tracking efficiency. The experimental results show that the proposed MPPT circuit has up to 98.7% maximum power tracking efficiency. Besides, the energy storage circuit is designed to prevent the load from power failure in some cases.

Acknowledgments

This work was supported by Zhejiang Provincial Natural Science Foundation of China (Grant LY20F010003, Grant LZ20F010006), Natural Science Foundation of Ningbo (Grant 2019A610113), the National Natural Science Foundation of China (Grant 61801253, Grant U1709218, Grant 61971389) and K.C.Wong Magna Fund in Ningbo University.

References

[1] R. J. M. Vullers, et al.: “Energy harvesting for autonomous wireless sensor networks,” IEEE Solid-State Circuits Mag. 2 (2010) 29 (DOI: 10.1109/MSSC.2010.936667).
[2] R. J. Vullers, et al.: “Micropower energy harvesting,” Solid-State Electron. 53 (2009) 684 (DOI: 10.1016/j.ssc.2008.12.011).
[3] D. Porcarelli, et al.: “Adaptive Rectifier Driven by Power Intake Predictors for Wind Energy Harvesting Sensor Networks,” IEEE J. Emerg. Sel. Topics Power Electron 3 (2015) 471 (DOI: 10.1109/JESTPE.2014.2316527).
[4] T. Ogawa, et al.: “20 mV input, 4.2 V out put boost converter with methodology of maximum output power for thermoelectric energy harvesting,” IEEE APEC (2016) 1907 (DOI: 10.1109/APEC.2016.7468129).
[5] C. Knight, et al.: “Energy options for wireless sensor nodes,” Sensors 8 (2008) 8037 (DOI: 10.3390/s8120837).
[6] Liang Junnui, et al.: “Impedance Modeling and Analysis for Piezoelectric Energy Harvesting Systems,” IEEE/ASME 17 (2012) 1145 (DOI:10.1109/tmech.2011.2160275).
[7] Hua Yu, et al.: “A Vibration-Based MEMS Piezoelectric Energy Harvester and Power Conditioning Circuit,” Sensors 14 (2014) 3323 (DOI:10.3390/s140203323).
[8] E. Lefeuvre, et al.: “A comparison between several vibration-powered piezoelectric generators for stand-alone systems,” Sensors 126 (2006) 405 (DOI: 10.1109/jssc.2005.10.043).
[9] Y. K. Ramadass, A. P. Chandrakasan: “A battery-less thermoelectric energy harvesting interface circuit with 35 mW startup voltage,” IEEE J. Solid-State Circuits 46 (2011) 333 (DOI: 10.1109/JSSC.2010.2074090).
[10] Y. K. Ramadass, A. P. Chandrakasan,: “An Efficient Piezoelectric Energy Harvesting Interface Circuit Using a Bias-Flip Rectifier and Shared Inductor,” IEEE J. Solid-State Circuits 45 (2010) 189 (DOI: 10.1109/JSSC.2009.2034442).
[11] Yi Die Ye, et al.: “A self-powered zero-quiets-current active rectifier for piezoelectric energy harvesting,” IEICE Electron. Express 15 (2018) 20180739 (DIO: https://doi.org/10.1587/elex.15.20180739).
[12] Ottman, et al.: “Optimized piezoelectric energy harvesting circuit using step-downconverter in discontinuous conduction mode,” IEEE Trans. Power Electron 18 (2002) 1988 (DOI: 10.1109/
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A Piezoelectric Energy Harvesting System with Parallel-SSH Rectifier and Integrated MPPT Achieving 417% Energy-Extraction Improvement and 97% Tracking Efficiency; IEEE VLSI Circuits (2019) 18868040 (DOI: 10.23919/VLSIC.2019.8778144).

Chi-Huan Chen, et al.: “A series-SSH-Phi interface circuit for piezoelectric energy harvesting with 163% improvement in extracted power at off-resonance,” A-SSCC (2016) 16657241 (DOI: 10.1109/ASSCC.2016.7844127).

Adrien Morel, et al.: “A Shock-Optimized SECE Integrated Circuit,” IEEE J. Solid-State Circuits 53 (2018) 3420 (DOI: 10.1109/JSSC.2018.2868299).

Jabbar Hamid, et al.: “Piezoelectric Energy Harvester Impedance Matching Using a Piezoelectric Transformer,” Sensors (2017) 17024424716304885 (DOI: 10.1016/j.sna.2017.07.036).

Chen Nan, et al.: “A piezoelectric impact-induced vibration cantilever energy harvester from speed bump with a low-power power management circuit,” Sensors 254 (2017) 134 (DOI: 10.1016/j.sna.2016.12.006).

Chen Nan, et al.: “Alternating Resistive Impedance Matching for an Impact-Type Microwind Piezoelectric Energy Harvester,” IEEE Trans. Ind. Electron. 65 (2018) 7374 (DOI: 10.1109/TIE.2018.2793269).

Saggini Stefano, et al.: “Implementation of reactive and resistive load matching for optimal energy harvesting from piezoelectric generators,” IEEE COMPEL (2010) 28 (DOI: 10.1109/COMPEL.2010.5562431).

Z. J. Chew, M. Zhu: “Adaptive Maximum Power Point Finding Using Direct VOC/2 Tracking Method With Microwatt Power Consumption for Energy Harvesting,” IEEE Trans. Power Electron 33 (2018) 8164 (DOI: 10.1109/tpele.2017.2774102).

D. H. Jung, et al.: “Thermal and solar energy harvesting boost converter with time-multiplexing MPPT algorithm,” IEICE Electron. Express 13 (2016) 20160287 (DOI: 10.1587/elex.13.20160287).

N. Kong, D. S. Ha: “Low-Power Design of a Self-powered Piezoelectric Energy Harvesting System With Maximum Power Point Tracking,” IEEE Trans. Power Electron 27 (2012) 2298 (DOI: 10.1109/TPEL.2011.2172960).

Stanzione S, et al.: “A High Voltage Self-Biased Integrated DC-DC Buck Converter With Fully Analog MPPT Algorithm for Electrostatic Energy Harvesters,” IEEE J. Solid-State Circuits 48 (2013) 3002 (DOI: 10.1109/jssc.2013.2283152).

Y. K. Teh, et al.: “Design of transformer-based boost converter for high internal resistance energy harvesting sources with 21 mV self-startup voltage and 74% power efficiency,” IEEE J. Solid-State Circuits 49 (2014) 2694 (DOI: 10.1109/JSSC.2014.2354645).

Sangkwon Lee, Jinseong Jeong: “An off-chip input capacitor-less boost converter with fast MPPT for energy harvesting,” IEICE Electron. Express 10 (2014) 20120906 (DOI: 10.1587/elex.10.20120906).

Shi, Ge, et al.: “An Efficient Power Management Circuit Based on