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Robust Control Algorithm for Piezo-electric Energy Scavenging

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Abstract

The paper proposes a robust control algorithm for the piezoelectric energy scavenging in the presence of uncertainties. The nonlinear dynamics makes the piezoelectric actuators unstable and shows substantial uncertainty and disturbances in the output. In this study a closed loop step down DC–DC converter along with the Extended State Observer (ESO) is implemented. This paper proposes step by step design of buck converter and its linear mathematical model. The output of a buck converter is taken as a feedback along with the heuristic implementation of ESO. Extended state observer is designed such that it estimates the state and lumped uncertainties. The proposed algorithm is addressed to maintain the output voltage constant in the piezoelectric energy harvester under the uncertainties. The efficacy of the proposed algorithm is verified using MATLAB Simulink and the result shown in this paper showcase a better voltage regulation in the presence of uncertainties and wide range of dynamic input voltage.

Keywords- Buck Converter, Extended State Observer (ESO), Piezoelectric Energy Scavenging

1. Introduction

The demand for renewable energy sources is increasing day by day. The process of the conversion of renewable energy into electrical energy is referred to as energy scavenging and it can be utilized in many applications including portable electronics, wireless gadgets and power systems Lu et al., 2010. Energy harvester is used to recharge the battery and the input for the harvester is dynamic, as it is obtained from environmental energy sources such as sunlight, wind, etc. Lu et al., 2010. Different energy harvesting methodologies are available such as piezoelectric Ayrikyan et al., 2017, wind Wu et al., 2013, thermoelectric Hu et al., 2020 and solar Carvalho and Paulino, 2010. Because of better liberal vibration accessibility and good harvesting material property, piezoelectric energy harvesting based method is selected Ayrikyan et al., 2017.

In piezoelectric approach, due to unstable vibration status the output voltage is also changing Grace et al., 2011. In order to scavenge as much energy as possible, a run-time adaptive mechanism is required to track the output voltage with the vibration of piezoelectric element Chao et al., 2007. Energy scavenging systems provide constant output voltage with the growing application of DC–DC converter Gundecha et al., 2016,

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Nguyen et al., 2021. The piezoelectric sensors are used to stimulate the development of specific converters to operate such actuators Bellmunt et al., 2007. Different switching converter topologies have been employed to drive such actuators, buck Lakshmi and Raj, 2014, boost Gundecha et al., 2016, and buck-boost Lefeuvre et al., 2007.

The voltage in the output cannot be considered as constant and it should be controlled by different strategies. A variety of controlling strategies like PID controller Djmel et al., 2019, fuzzy logic Ardhenta et al., 2020, and sliding mode control Utomo et al., 2020 are available to control the power converter. The effects of uncertainties and disturbance in control are estimated by introducing some observing methods like disturbance observer (DO), State and disturbance observer (SDO) Chavan et al., 2019, Discrete Kalman Filter and High Gain Observers Ali et al., 2019, H_∞ Wang et al., 2020, Luenberger Observer Wang and Li, 2020. Extended state observer (ESO) Han, 2009 is a better observing technique that can estimate both state as well as disturbance with less plant information Li et al., 2011. The ESO is used to estimate the present uncertainty and disturbance in order to minimize the effect in the output Bin et al., 2014. ESO has been widely applied in various areas like motion control systems Mahapatro et al., 2019, robot control systems Ma et al., 2020 and vibrations Shi et al., 2021.

Based on the literature, most commonly used control algorithms and the observers are listed in Table 1.

Table 1. Literature on control algorithms & observers

Control Algorithms	**Observers**	
PID Control	Disturbance Observer (DO)	State & Disturbance Observer (SDO)
Sliding Mode Control (SMC)	High Gain Observers	Discrete Kalman Filter Observers
Fuzzy Logic Control	$H\infty$ Observer	

The rest of the paper is organized as follows: Section 2 introduces piezoelectric energy scavenging system. Section 3 describes the operation of a DC–DC buck converter. Section 4 gives the mathematical modelling of DC–DC buck converter. Section 5 explains the concept of control design. The results are shown with related discussion in section 6. The paper is concluded in section 7.

2. Piezoelectric Energy Scavenging

Piezoelectric materials are used for energy scavenging to convert mechanical strain into an electrical form due to their small size and the piezoelectric effect. The equivalent circuit of a vibrating piezoelectric element can be modeled as a source of sinusoid current $i_P(t)$ parallel to its C_p electrode capacitor.

AC–DC rectifier is required as the output of piezoelectric material is an AC signal. The magnitude of the polarization current I_p depends on the level of mechanical excitation of the piezoelectric element, frequency of mechanical vibration and hence the rectifier voltage may not be constant Ottman et al., 2003. The ability to achieve and maintain constant output voltage is accomplished by placing a DC–DC step-down converter between the rectifier and the electronic load as shown in Fig.1. A DC–DC step-down converter is known as buck converter. A buck converter is placed between the rectifier and the electronic load. The control approach used an extended state observer (ESO) for estimating state as well as lumped disturbance. This strategy gives constant and regulated output voltage by using ESO in the presence of certain uncertainties.

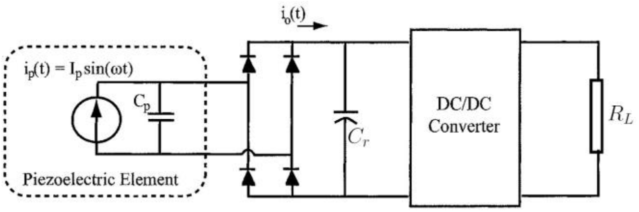

Fig. 1. Energy harvesting circuitry

The DC component of the output current and the rectifier capacitor voltage give the power of the piezoelectric element Ottman et al., 2003 are shown as;

$$i_0(t) = \frac{2I_p}{\pi} - \frac{2V_r\omega C_p}{\pi} \qquad P(t) = \frac{2V_r}{\pi}\left(I_p - V_r\omega C_p\right)$$

Where V_r is the rectifier capacitor voltage and ω is the resonating frequency.

The controller of the converter is designed to achieve and maintain the constant output voltage in presence of the uncertainties. The output obtained from the piezoelectric sensor is characterized and studied for selection of proper voltage levels for further interface. The frequency of vibration plays an important role in the generation of the corresponding electrical voltage Ottman et al., 2003, Volture. The characteristics of a piezoelectric sensor when operated in different conditions are shown in Table 2. The tip mass range is considered from *0 gram* to *7.8 gram* and their corresponding variation in frequency, AC voltage and rectified DC voltage is stated in Table I. The system efficiency depends on the rectification output in conjunction with the DC-DC converter. A step down converter is used to maintain the constant output voltage.

Table 2. Characteristics of piezoelectric sensor

Tip Mass *(gram)*	**Frequency** *(Hz)*	**Open Ckt. Vtg** *(rms)*	**Rectified O/P** *(V_{dc})*	**Tip Mass** *(gram)*	**Frequency** *(Hz)*	**Open Ckt. Vtg** *(rms)*	**Rectified O/P** *(V_{dc})*
0	120	3.2	3.11	2.4	75	6.5	7.7
0	120	4.4	4.8	2.4	75	7.5	9.17
0	120	5.5	6.3	2.4	75	11.5	14.81
0	120	10.1	12.84	7.8	50	10.3	13.12
2.4	75	4.7	5.22	7.8	50	15.4	20.31

3. Buck Converter

Buck converter is referred to as step down converter. In a buck converter, an unregulated DC input voltage is converted to a regulated low DC output voltage. A typical buck converter is shown in Fig 2. The buck converter comprises a power MOSFET Ramirez et al., 2006 used as a controllable switch *Q* with two states $\mu = 0$ and $\mu = 1$, a diode *D*, an inductor *L*, and a filter capacitor. The buck converter is connected to a DC source which is rectified from piezoelectric output of voltage *E* that provides a regulated DC voltage V_o to the load resistor *R*.

When the MOSFET *Q* is ON, the diode *D* is reversed biased and the input current, I_L flows through the inductor *L* and resistor *R*. When the MOSFET *Q* is OFF, the diode *D* gets conducted and the inductor current flows through the inductor, capacitor and resistor.

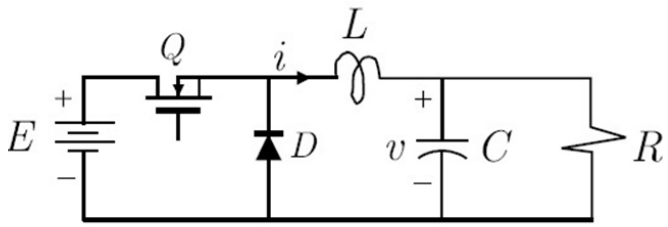

Fig. 2. Circuit diagram of buck converter

Therefore the output voltage depends on the input voltage, duty cycle and it is always less than the input voltage. The inductor value depends upon the frequency, load and ripple current, input and output voltages Lakshmi and Raja, 2014. Designing a good performance buck converter, the inductor ripple current should lie between 10% to 20% of the output current. The output voltage ripple is the most important criterion for selecting the capacitors.

The output voltage, value of inductance and capacitor are given as;

$$V_0 = E \times d \qquad L = \frac{(E - V_{out}) \times d}{f_s \times \Delta I_L} \qquad C = \frac{I_L}{8 \times f_s \times \Delta V_{out}}$$

Where *d* is the duty cycle.

4. Modeling of Buck Converter

Consider the ideal configuration as shown in Fig. 2, to describe the dynamics of DC-DC buck converter. The mathematical modeling of a DC-DC buck converter is based on the controlling action of switch Wang et al., 2015.

When the switch is ON (i.e. at $\mu = 1$), the equation is obtained by applying Kirchhoff's laws to the circuit shown in Fig. 2.

$$\frac{di_L}{dt} = \frac{E - V_0}{L} \tag{1}$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \tag{2}$$

Where i_L is the inductor current and V_0 is the output voltage.

When the switch is OFF (i.e. at $\mu = 0$), the equation is obtained by applying Kirchhoff's laws to the circuit shown in Fig. 2.

$$\frac{di_L}{dt} = \frac{-V_0}{L} \tag{3}$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC}$$

Then combining equation *(1)*, *(2)*, *(3)*, *(4)* and when $\mu \in [0, 1]$, the average model can be written as;

$$\frac{di_L}{dt} = \frac{\mu E - V_0}{L} \tag{5}$$

$$\frac{dV_0}{dt} = \frac{i_L}{C} - \frac{V_0}{RC} \tag{6}$$

In practice, the load resistance may vary and the assumed nominal value of *R* is R_0.

Let $z_1 = (V_0 - V_{ref})$ and $z_2 = \left(i_L/C\right) - \left(V_0/R_0C\right)$ be the state variables, hence the model is rewritten as;

$$\dot{z}_1 = \frac{i_L}{C} - \frac{V_0}{RC} + \varphi_1(t) \tag{7}$$

Where $\varphi_1(t) = -\frac{V_0}{RC} + \frac{V_0}{R_0C}$ is the mismatched disturbance.

Therefore;

$$\dot{z}_2 = \frac{\mu E - V_0}{LC} - \frac{1}{R_0C}\left(\frac{i_L}{C} - \frac{V_0}{RC}\right) \tag{8}$$

It can be simplified as;

$$\dot{z}_2 = \frac{\mu E - V_{ref}}{LC} - \frac{z_1}{LC} - \frac{1}{R_0C}\left(\frac{V_0}{R_0C} - \frac{V_0}{RC}\right) \tag{9}$$

Denoting; $u = \frac{\mu E - V_{ref}}{LC}$ and $\varphi_2(t) = -\frac{1}{R_0C}\left(\frac{V_0}{R_0C} - \frac{V_0}{RC}\right)$

The model can be simplified using equation *(7)* and *(9)* as;

$$\dot{z}_1 = z_2 + \varphi_1(t) \tag{10}$$

$$\dot{z}_2 = u - \frac{z_1}{LC} - \frac{z_2}{R_0C} + \varphi_2(t) \tag{11}$$

5. Control Design

A robust control for variable load in a DC-DC buck converter is designed in this section with a piezoelectric energy scavenging system. The ESO is used to estimate two states as well as disturbance Han, 2009. A proposed control configuration is shown in Fig. 3.

Consider the mismatched disturbance estimation of $\varphi_1(t)$, based on the ESO technique is designed as;

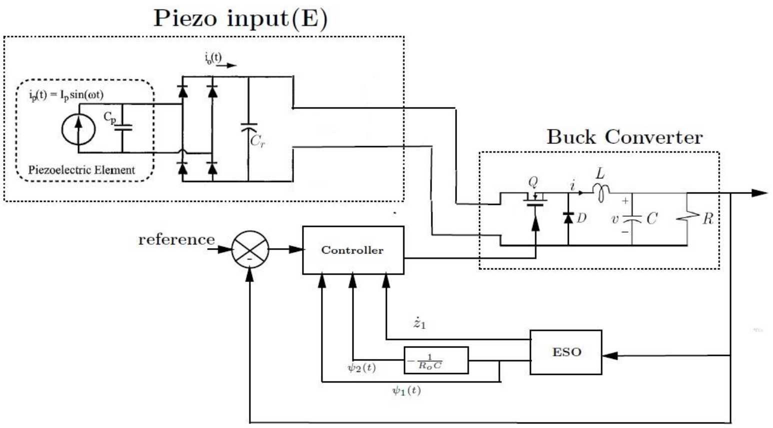

Fig. 3. Proposed control configuration

$$\dot{\hat{z}}_1 = \hat{z}_2 + z_2 - \beta_1(\hat{z}_1 - z_1) \tag{12}$$

$$\dot{\hat{z}}_2 = -\beta_3(\hat{z}_1 - z_1) \tag{13}$$

Where, $z_1 = \hat{z}_1$, $z_2 = \hat{\varphi}_1(t)$ and $\beta_1 > 0$, $\beta_2 > 0$.

From the equation *(7), (8), (9)* and *(10)* the relationship between φ_1 and φ_2 is given by;

$$\hat{\varphi}_2(t) = -\frac{1}{R_0C}\hat{\varphi}_1(t) \tag{14}$$

In a buck converter, ESO is employed to observe and estimate the disturbance φ_i of a plant and which is based on control input and plant output. The proposed ESO-based system under mismatched disturbance is designed in Gundecha et al., 2016, Mahpatro et al., 2015 as;

$$u = \left[\frac{z_1}{LC} + \frac{z_2}{R_0C} - \hat{\varphi}_2 - k_1\hat{z}_1 - k_2(z_2 + \hat{\varphi}_1)\right] \tag{15}$$

6. Results and Discussion

The proposed algorithm has been tested for voltage tracking in a buck converter with piezoelectric energy scavenging system. The responses of variable output load resistance and dynamic changes in input voltage are tested on the propose algorithm.

The proposed work is used to control and analyse the effect of dynamic variation in piezoelectric input. From Ottman et al., 2003 the trajectory as shown in Fig. 4(a) is designed. For variable input voltage *E,* the load resistance is changed from *200*Ω to *150*Ω. From Fig. 4(b), it is observed that the controller design in equation *(11)* estimates the changes in the state and adjusts the duty cycle for getting output voltage at *4.5V*.

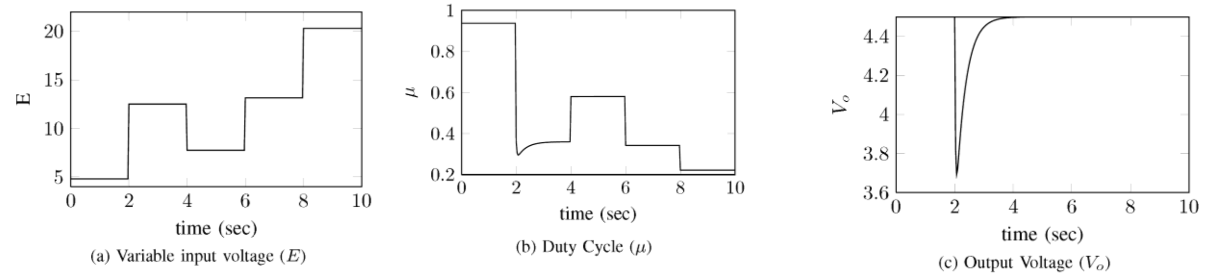

Fig. 4. Dynamic variation in piezoelectric input

Case 1: Variable Load Resistance (R_L)

The buck converter is evaluated under variable load resistance conditions for tracking the reference voltage. The input voltage is considered as, $E = 8V$, reference voltage as, $V_{ref} = 4.5V$. The tracking and estimation performance for *180*Ω resistance is shown in Fig. 5. The duty cycle (μ) and the controlled output are shown in Fig. 5(c), 5(d). The results are tested for different R_L range from 140Ω to 240Ω. The cumulative results for *Case 1* are illustrated in Table 3.

Table 3.Performance result for variable load resistance

R_L (Ω)	μ (V_{rms})	Tracking Error $(z_1 = V_{ref} - V_0)$	Estimation Error $(e = z_1 - \hat{z}_1)$	R_L (Ω)	μ (V_{rms})	Tracking Error $(z_1 = V_{ref} - V_0)$	Estimation Error $(e = z_1 - \hat{z}_1)$
180	0.5466	0	0.0026	230	0.5861	0	0.0051
200	0.5777	0	0.0031	240	0.5962	0	0.0076

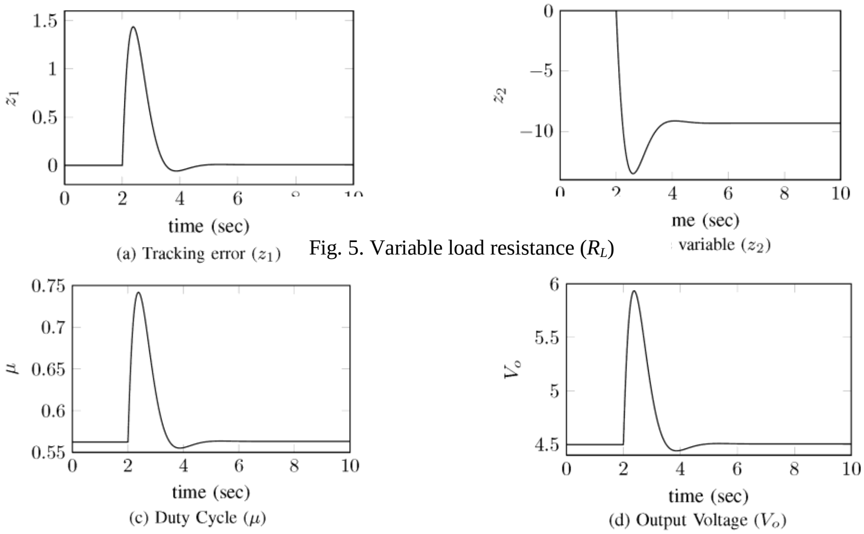

Fig. 5. Variable load resistance (R_L)

Case 2: Variable Input Voltage (E)

The estimation and tracking performance for an input voltage is tested for different E range from *8V* to *16V*. The results are illustrated in Table 4.

Table 4.Performance result for variable input voltage

E (V)	**μ** (V_{rms})	**Tracking Error** ($z_1 = V_{ref} - V_0$)	**Estimation Error** ($e = z_1 - \hat{z}_1$)	**E** (V)	**μ** (V_{rms})	**Tracking Error** ($z_1 = V_{ref} - V_0$)	**Estimation Error** ($e = z_1 - \hat{z}_1$)
8	0.5548	0	0.0013	12	0.3698	0	0.0013
10	0.4438	0	0.0013	14	0.3170	0	0.0013

Case 3: Variable Reference Voltage (V_{ref})

The reference voltage is varied from *3.8V* to *5.8V* and the load resistance R_L= *200* with the input voltage *E=8V*. The proposed controller is suitable to regulate the required output voltage. The results for variable reference varied from *3.8V* to *5.8V* are shown in Table 5.

Table 5.Performance result for variable reference voltage

V_{ref} (V)	**μ** (V_{rms})	**Tracking Error** ($z_1 = V_{ref} - V_0$)	**Estimation Error** ($e = z_1 - \hat{z}_1$)	V_{ref} (V)	**μ** (V_{rms})	**Tracking Error** ($z_1 = V_{ref} - V_0$)	**Estimation Error** ($e = z_1 - \hat{z}_1$)
3.8	0.4685	0	0.0011	4.5	0.5548	0	0.0013
4.0	0.4931	0	0.0012	5.8	0.7150	0	0.0017

The proposed work shows the robust voltage tracking of buck converters for piezoelectric energy harvesting and the results are verified in simulation. The different cases of the piezoelectric energy scavenging are considered and obtain better voltage tracking results with various dynamic constants. The effects of disturbances are compensated by ESO, caused by load and input uncertainties.

7. Conclusions

The paper proposed a robust control approach for DC– DC buck converter for scavenging electrical energy from a mechanically excited piezoelectric element. The disturbances caused by variation in load and input are compensated by using ESO. A good disturbance rejection against input and load resistance variation is obtained with better voltage tracking performance and state estimation. A robust control strategy with application to piezoelectric energy scavenging for uncertain dynamics is confirmed.

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