An improved switching control law for the optimized synchronous electric charge extraction circuit

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Abstract. Nonlinear switching interface circuits are considered as an efficient way to improve the performance of vibration energy harvesters. Among the various approaches, OSECE (Optimized Synchronous Electric Charge Extraction) exhibits satisfying properties: simple switching strategy, good performance in low coupling cases and low load dependency. However, the overdamping induced by the voltage inversion at maximal points leads to performance degeneration in high coupling cases. This paper presents an improved switching control law for the OSECE technique. The new OSECE_PT (OSECE with switching Phase Tuning) technique presented here is to let the switches act ahead or after the maximal point with a phase tuning. Theoretical analysis and numerical simulations show that the OSECE_PT technique can improve the power performance effectively and preserves desired load independence properties.

1. Introduction
Autonomous WSN (Wireless Sensor Network) with the self-regenerated power source is expected in great demand. It allows the WSNs to get rid of the restriction of the battery and prolong the working life to a new record. Vibration energy harvesting is one of the most promising solutions to be embedded in WSN nodes to realize the power regenerating ability [1]. In order to ensure the robustness of the WSN node, the VEH (Vibration Energy Harvester) is required to provide a considerable level of power output under variable environmental vibrations. It contains two aspects: First, the vibration generator part of the VEH has to be wideband [2, 3]; Second, the interface circuit must be capable of extracting the electric power with high performance for different load situations.

Due to the standard circuit’s poor performance in low coupling cases and its high load dependence, nonlinear switching interface circuits [4-5] are considered as an efficient way to improve the performance of vibration energy harvesters. Among the various approaches, OSECE presented in figure 1 (a) shows satisfying properties: simple switching strategy, good performance in low coupling cases and low load dependency [6]. However, the overdamping induced by the voltage inversion at maximal points leads to performance degeneration in high coupling cases when the ratio of the extracted energy in a period exceeds the optimal point [7, 8]. A new controller introducing switching pauses has been proposed for the overdamping effect of the SSHI (Synchronous Switching Harvesting on Inductor) circuit with a constant load in high coupling cases [9].

In this paper, an improved switching control law for the OSECE named as OSECE_PT is proposed. Analytical and numerical analysis shows that the OSECE_PT approach can keep the optimal power performance in high coupling cases and low load dependence at the same time.
2. Improved control law for OSECE

2.1. OSECE circuit
Before starting the discussion of the interface circuit, the general electromechanical model of a linear piezoelectric generator can be written as:

\[
\begin{align*}
M\ddot{u} &= F - Ku - \mu \dot{u} - \alpha V \\
I &= \alpha \ddot{u} - C_0 \dot{V}
\end{align*}
\]  \hspace{1cm} (1)

in which \(M\) is the inertial mass, \(F\) the excitation force, \(u\) the displacement, \(K\) the stiffness, \(\mu\) the damping coefficient, \(\alpha\) the piezoelectric force factor, \(V\) the piezoelectric voltage, \(I\) the current out of the piezo element and \(C_0\) the piezo element’s capacitance.

When the OSECE circuit is used for extracting the electric energy of the generator’s piezo element as shown in figure 1 (a), the operation principle is explicated as follows: As the displacement \(u\) and the in-phase piezoelectric voltage \(V\) reach the positive maximum point, switch \(S_1\) is closed while \(S_2\) is kept open. A \(LC\) oscillation starts and the energy is returned to \(C_0\) with the voltage \(V\) inverted. Once \(V\) reaches \(-V_{DC}/m\) (\(m\): turn ration of the transformer; \(V_{DC}\): load voltage), the remained energy in \(L_1\) goes to the load side. Subsequently, the piezoelectric voltage decreases with \(u\). As \(V\) arrives at the negative maximum, the status of the switches are inverted (\(S_1\) open, \(S_1\) closed). A similar process as half period 1 is started.

Due to the presented inverted piezoelectric voltage as an offset for the charge accumulation in the piezoelectric, more power can be harvested in low coupling cases. However, it imposes an overdamping effect and reduces the available power in high coupling cases. This performance degeneration trend is clearly seen from the normalized max power curve versus the coupling figure \(k^2Q_m\) \((k^2\): electromechanical coupling level, \(Q_m\): mechanical quality factor of the generator) in figure 3.

![Figure 1. (a) OSECE circuit; (b) Phase tuning operation and waveforms of OSECE_PT circuit.](image)

2.2. OSECE_PT technique
The new OSECE_PT (OSECE with switching Phase Tuning) technique presented here is to let the switches act ahead or after the maximal point with a phase tuning value \(\phi_T\) as indicated by the waveforms in figure 1 (b). During the period between the maximum voltage point and the switching point, the energy stored on the piezo element is returned to dynamic system. Consequently, the energy extracted from the piezoelectric transducer can be controlled by altering \(\phi_T\).

Following the approach in [6], the extracted energy in each switching operation can be expressed as:

\[
E_{\text{extr}} = \frac{V_{DC}^2}{R_t} \frac{\pi}{\omega} = \frac{1}{2} (C_0V_M^2 \sin^2 \phi_0) e^{\frac{\phi_T}{Q_t}}
\]  \hspace{1cm} (2)

where \(\phi_0\) is the end phase of the \(LC\) oscillation, \(Q_t\) is the quality factor of \(LC\) circuit, \(\omega\) is the excitation frequency and other variables defined in figure 1. We also have:
Eq. (4) is obtained by integrating the electric part of eq. (1) for a half period between two switching actions \((I=0)\) while eq. (5) is from energy balance relationship. Using eqs. (2)-(5), we can write the power expression as:

\[
P_{\text{OSECE}_{-}\text{PT}} = \frac{2(\alpha \cos \phi_i)^2}{\pi C_o \omega} \sin^2 \phi_i e^{\frac{\phi_i}{2\Omega}} \left[1 + \cos \phi_i e^{\frac{\phi_i}{2\Omega}}\right] F^2_m \left[\frac{\mu + 4(\alpha \cos \phi_i)^2}{\pi C_o \omega} \left[1 + \cos \phi_i e^{\frac{\phi_i}{2\Omega}}\right]\right]
\]

\((6)\)

\(F_m\) is the amplitude of the excitation force. When normalized by the maximum available power \(P_{\text{max}}=F_m^2/8\mu\) [10], we have the normalized expression:

\[
P_{\text{OSECE}_{-}\text{PT}}' = \left[\frac{\sin^2 \phi_i e^{\frac{\phi_i}{2\Omega}}}{\left[1 + \cos \phi_i e^{\frac{\phi_i}{2\Omega}}\right]^2}\right] \left[\frac{\mu + 4(\alpha \cos \phi_i)^2}{\pi C_o \omega} \left[1 + \cos \phi_i e^{\frac{\phi_i}{2\Omega}}\right]\right] F^2_m \left[\frac{\pi k^2 Q_o \cos^2 \phi_i}{\left[1 + \cos \phi_i e^{\frac{\phi_i}{2\Omega}}\right]^2}\right]
\]

\((7)\)

It is interesting to find that \(k^2 Q_o\) is multiplied by an additional coefficient \(\cos^2 \phi_i\) when comparing with the normalized expression of OSECE in [6]. It is inferred that tuning the switching phase ahead or after the original maximum voltage (displacement) amount to decrease the coupling level \(k^2\) by a factor of \(\cos^2 \phi_i\). In this way, the figure \(k^2 Q_o\) can be controlled at the optimal level avoiding to overdamp the system responses.

**Figure 2.** (a) Normalized maximal power versus \(k^2 Q_o\) and \(\phi_i\) with optimal power points highlighted in pink; (b) Corresponding optimal normalized load.
\((\xi_e=2R_L \omega C_0 / \pi)\) is also plotted versus \(k^2 Q_m\) and \(\phi_f\) in figure 2 (b) with the values corresponding to the optimal power points marked by the pink lines as well. The load resistance goes small as \(k^2 Q_m\) increases and approaches to zero with \(k^2 Q_m > \pi/4\).

Figure 3. Normalized max power comparison between OSECE_PT and other approaches.

Figure 4. Normalized power versus different load and coupling cases.

Figure 3 presents the optimal normalized power for several often used approaches. The OSECE_PT approach has the best performance for low \(k^2 Q_m\) values as the OSECE technique and maintains the best performance for high \(k^2 Q_m\) values. A performance boost of \(\Delta P\) is observed when compared with OSECE. Moreover, the load dependence of OSECE_PT is also investigated as shown in figure 4 with OSECE for comparison. Obviously, the desired weak load dependence is preserved.

3. Numerical validation

3.1. LTSpice Model

In order to validate the performance of the OSECE_PT technique, an approach of utilizing the equivalent network instead of the mechanical dynamic system is used. Consequently, the harvester system composed of a linear piezoelectric generator and the OSECE_PT circuit can be represented by the Spice model in figure 5. The switching control signal generation part which provides a square waveform with a phase shift to the piezoelectric voltage is not shown here. With the model realized in the LTspice© software, numerical simulations are performed for different \(k^2 Q_m\) and load resistance cases (turn ratio m=4). In order to simplify the analysis, the diode in the circuit is assumed as an ideal unidirectional component with zero forward voltage and very small conducting resistance.

Figure 5. Schematic figure of the LTSpice© Model.

3.2. Results

By varying the switching phase and the load, simulations are repeated to search the optimal power points and the corresponding phase and load. Figure 6 (a) presents the maximum normalized power obtained from the simulation. The numerical results are in good agreement with the theory. The deviation is due to the inadequate simulation time and the decreased \(Q_f\) in the low coupling cases. As
can be seen, the performance is stabilized around the optimal value after the coupling is greater than a certain value. The optimal switching phase is also obtained with only the phase-lag ($\phi_T>0$) branch considered in figure 6 (b). The numerical results confirms the theory well again.

With the optimal phase determined, the load dependence of OSECE_PT is studied by changing the load in a wide range. Figure 6 (c) shows the available normalized power for different cases. As predicted in theory, the weak load dependence is observed. Moreover, the load independence can be further improved by increasing the turn ratio of the transformer in the circuit [6].

Figure 6. Numerical simulation results for the OSECE_PT technique: (a) Maximum normalized power; (b) Optimal switching phase $\phi_T$; (c) Normalized power for different load and $k^2Q_m$.

4. Conclusion

In this paper, an improved switching control law for the OSECE technique is presented. It is to let the switches act ahead or after the maximal point with a phase tuning. Theoretical analysis and numerical simulations show that the OSECE_PT technique can improve the power performance effectively and preserves desired load independence properties. This is an outstanding advantage over the standard circuit, especially in the wideband energy harvesting applications where the load matching is difficult to achieve. Another important advantage is the expected bandwidth widening effect as presented in [11] for SECE circuit. It is understood that the OSECE_PT technique can greatly extend the application area to all coupling level cases while the tuning realization is easily feasible with an autonomous circuit as shown in [12].

References

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