

ABSTRACT

Over the past two decades, advances in microelectronics and micro-electrical mechanical system (MEMS) technology have led to development of miniature devices for various applications which can run on micro to nano-watt power. This has ushered a growing interest in the field of energy harvesting using piezoelectric devices, which can convert dynamic mechanical strain into electric power in this range. In this connection, vibrations generated from civil structures, such as long/short-span bridges, city flyovers and elevated metro corridors, which are constantly under dynamic loads, are of special interest to researchers owing to the continuous availability of vibrations, unlike the solar power. The piezoelectric energy harvesters can work as sustainable and green power sources for ultra-low power consuming MEMS based portable electronic devices, such as wireless sensor nodes (WSNs), employed in automation systems, transportation networks, environmental monitoring, implanted medical devices and structural health monitoring (SHM). These can substitute batteries, which not only suffer from a finite lifespan but also pose environmental issues during disposal. Today, piezoelectric energy harvesting (PEH) represents a promising emerging technology to achieve autonomous, self-powered, and maintenance-free operation of WSNs and similar devices. However, several practical impediments still hinder the real-life deployment of PEH devices on civil infrastructures, such as low-frequency of the available vibrations (typically < 5 Hz) encountered there, coupled with low levels of voltage generation and the erratic nature signals.

The vast majority of PEH-related studies so far have only focused on the configurations and geometries of the harvester, often entailing secondary structures. d_{31} mode, which is the most

natural mode of excitation, has not been investigated in depth for piezo-patches directly bonded to the main structure. Such studies, which have focused on electronic conditioning circuitry for energy extraction, have been typically restricted to high sinusoidal voltages (>10 V) and high frequency (>20 Hz) signals or when the piezoelectric energy harvester is continuously excited in resonance conditions. However, very limited research has been carried out for low-frequency (<5 Hz) and low-voltage scenarios (<2 V) or where changes in excitation frequencies and voltage magnitudes are frequent, such as in case of real-life structural vibrations. Therefore, a successful industrial-scale deployment of PEH technology on civil-structures is still not operationally realized. The other important aspect is storage, which is problematic in civil-structures, again owing to their low-frequencies and erratic nature of vibrations.

This doctoral thesis aims to address these challenges and investigate power electronic interface circuits to enhance the power output and storage of the piezoelectric energy harvesters from civil infrastructure. Firstly, the experiments were carried out on a real-life city flyover to facilitate a first-hand measurement of the frequency range and the possible voltage range generated from surface-bonded Lead zirconate titanate (PZT) patches. This helped in understanding gaps between the lab and a typical real-life structure. With this information, further experiments were conducted in laboratory simulating real-life conditions of frequency and voltage pattern to perform a parametric study for investigating the influence of factors such as vibration frequency, voltage and circuit components like diodes on the harvestable power, otherwise not possible in real-life situations. Two standard bridge rectifier circuits: one using silicon diodes and the other using schottky diodes, were employed to charge a capacitor. From these experiments, it was established in principle that it is possible to harvest vibration power of the order of nano-watts

from a typical city flyover characterized with natural low-frequency. The schottky diode was found to perform better as compared to the silicon diode. Some power was also lost due to the voltage drop in the diodes of the rectifier.

The next set of experimental studies focused on evaluating various passive rectifier circuit topologies and zero on the best off the chip topology for the bridge rectifier circuits. The experiments were conducted using diode-based bridge rectifier circuit (DBRC) and metal-oxide semiconductor field effect transistor (MOSFET) based bridge rectifier circuit (MBRC). DBRC comprised of two different Schottky-type diodes (a) Model BAT1000 (b) Model IN-5819. MBRC comprised of a pair n-channel MOSFET (NMOS) and p-channel MOSFET (PMOS) in three different configurations, namely diode tied MOSFET (DMOS), gate cross-coupled MOSFET (GCMOS) and gate fully cross-coupled MOSFET (GFCMOS) connections in order to reduce the voltage drop during operations. The vibration signals were generated from a macro fiber composite (MFC) piezo patch bonded on a glass fibre composite cantilever beam. The cantilever was in-turn subjected under different excitation frequencies, but constant voltage amplitude, and vice-versa, to find each circuit's suitability for harvesting energy in real-life sources such as civil structures, where signals are characterized by low-frequency and low-voltage amplitude. The rectifier circuits were fully implemented using discrete components without involving any other external components and other associated start-up subsystems, as required in many of the previous reported studies.

Experimental results show that from PEH considerations, best performance is exhibited by D1000, a diode-based rectifier circuit, for the entire range of frequencies (5-15 Hz), which are

most dominant in civil-structures. The possible reason could be the lower forward bias voltage associated with D1000. Charging efficiency of about 81.33% has been achieved for 1 V open-circuit piezoelectric voltage excited at 5 Hz. The MOSFET based rectifier circuits, on the contrary, underperforms at 1 V, the possible reason could be the threshold voltage of the MOSFET is higher. Power in nano-watts range can be achieved across the capacitor from D1000 rectifier circuit at 5 Hz and 1 V open circuit voltage.

Next, an experimental laboratory investigation of the optimized D1000 rectifier circuit was carried out for charging a rechargeable battery from the energy harvested using piezoelectric element in simple d_{31} configuration. Lastly, field evaluation of the optimized circuit from the vibrations of the real-life city flyover and wind-based vibrations was carried out and storage of energy in the capacitor and battery was successfully demonstrated. A power of 0.17 mW was achieved from the MFC patch bonded directly to the girder and operating in d_{31} .

The main original contributions of this research have been to investigate and derive solutions for the practical issues related to PEH from low-frequency ambient vibrations of the civil-structures, which are otherwise good potential sources of vibrations. In this connection, the first contribution is the detailed investigation on circuit topologies by performing experiments under low-frequency and low-voltage scenarios typically encountered in real-life civil-structures. The second significant contribution is the proof-of-concept demonstration of PEH on real-life structures for the purpose of energy storage. It is expected that the study presented in this thesis can serve as a guideline for industrial scale design and manufacture of the piezoelectric energy harvesters for civil-infrastructure.