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Design of Piezoelectric Energy Harvester with an Adaptive MPPT for Efficient Power Extraction

D.Ezhilarasan [1], *G.Gokulraj* [2], *R.Madhumitha* [3]

[1]Department of Electronics and Communication Engineering, St. Joseph's College of Engineering, Chennai-600119, India
[2]Department of Electronics and Communication Engineering, St. Joseph's College of Engineering,Chennai- 600119, India
[3]Department of Electronics and Communication Engineering, St. Joseph's College of Engineering,Chennai- 600119, India

Abstract. This study presents a piezo electric energy harvester that includes a dedicated maximum power point tracking (MPPT) control scheme will be introduced to improve efficiency of energy harvesting using mechanical vibrations in the atmosphere because of the reduction of the impedance mismatch between piezo transducers and electronic devices. The general structure of the proposed harvester is a cantilever piezo transducer that is manufactured using lead zirconate titanate (PZT) ceramic and that has been optimized to operate at a resonant frequency of 60 Hz and a power moderator circuit that operates on less than 10 W and that includes a step-up voltage converter and a Schottky diode bridge rectifier. a microcontroller-based MPPT controller that is based on an adapted perturb-and-observe algorithm with adaptable step size; and an energy-store interface MPPT algorithm is continuously measuring the system voltage and current by using high-precision sensing circuits and dynamically controls the load impedance of the piezo transducer to the electrical load by using a digital potentiometer.
Keyword -- Energy harvesting technique, maximum power point tracking for improved power efficiency, piezoelectric transducers, mechanical stress, wireless sensor networks, power management, renewable energy source.

1 Introduction

The increased demand in the field of autonomous wireless sensor networks and Internet-of-Things (IoT) devices has spawned a strong need in the field of sustainable sources of power that can operate autonomously during a long period of time. Traditional battery-driven systems are limited by the exhaustible life span and maintenance requirements particularly in isolated or otherwise inaccessible places. Harnessing ambient energy provides a good way out to this predicament and piezoelectric energy harvesting is one technology that promises to transform the concept of electrical generation by converting the mechanical vibrations into electrical energy.

Piezoelectric substances produce electrical charge when subjected to mechanical force and because of this they are convenient in harnessing information in various forms of vibration such as the vibrations of machinery or mechanical stress, human as well as the vibrations in the environment. In the piezoelectric energy harvesters, however, impedance matching between piezoelectric element and electrical load has an important impact on the efficiency of the piezoelectric energy harvesters. The internal impedance of piezoelectric transducers depends on frequency, amplitude and environmental factors and therefore external optimization of the electrical load is required to maintain maximum power transfer. The methods of maximum power point tracking (MPPT) initially designed to operate electro voltaic systems have been effectively applied to various energy harvesting systems.

In piezoelectric systems, the MPPT algorithms constantly measure the characteristics of the output and adapt to the electrical load to maintain favourable power of the extraction conditions. The paper introduces a detailed design and construction of a piezoelectric energy harvesting device with an inbuilt MPPT functionality, which reveals its capability to increase power harvesting efficiency.

2 Literature Review

Current studies on piezoelectric energy harvesting have centred on optimizing the power collected, expanding the frequency band of use, and decreasing the control/conditioning overhead of working autonomous sensors. Literature could be divided into (a) foundational and review literature, (b) circuit and impedance-matching, (c) nonlinear and bandwidth-extension, (d) MPPT and adaptive-load, and (e) models and experimental validation - summarized below with major findings and limitations.

Original research and literature reviews define the field of application and overview technological issues. Roundy et al. analysed low level ambient vibration as credible sources of power to wireless sensor nodes and pointed out power conditioning and impedance-matching as the most practical limitations to useful harvested power. Surveys of piezoelectric harvesting technologies and MEMS-based applications made by Liu et al. and Tan et al. respectively, respectively, find trends, common power levels, and common failure points of ultra-low-power systems [6], [7], [9]. Lefeuvre et al. have compared multiple vibration-driven piezoelectric generators, which would give empirical baselines of generator topologies and exemplify trade-offs between output power and physical complexity of the generator [5].

There is a long strand of work on power-conditioning circuits and impedance matching since optimum loading of electrical circuits is very strongly sensitive to power transfer across transducer. Ottman et al. reported early adaptive harvesting circuitry functions, which were superior to simple resistive loading, and this dynamically adjusted the electrical load to track the properties of the transducer; the work led to the realization that cost of control energy overhead and tracking performance were closely coupled [10]. Dicken et al. have investigated the power-extraction circuits in miniature and low-power systems with a strong focus on the power-extraction design space, where the efficiency of extraction has to be compromised with the power consumption of the controller itself, which is highly important to resource-constrained nodes [8]. These circuit-level investigations are the inspiration to design that is good tracker and has a controller energy cost that is insignificant against the harvested energy.

In order to eliminate the narrow-band response of the linear harvesters, the nonlinear transduction and frequency-up conversion was investigated by multiple authors. Ferrari et al. showed that broadband excitation can be effectively used to excite nonlinear piezoelectric converters and broaden the bounds on energy harvesting of broader vibration spectra at the expense of more complex mechanical/electrical behaviour [12]. Erturk and Inman also presented an experimentally validated model bimorph cantilever that assists with the prediction of frequency response and geometry designs required to achieve desired resonance behaviour, which is a required step in the application of nonlinear or multi-modal harvester [15]. Mechanisms to increase the operating frequency ranges have been surveyed in Zhu et al (Multi-modal designs and tuneable structures) and Gu and Livermore (Impact-driven, frequency up-conversion mechanisms allowing effective harvesting of sub-resonant, low-frequency sources) [4], [11].

A second significant research direction is called Maximum Power Point Tracking (MPPT) and adaptive load-matching algorithms. Adaptive load-matching based on networks of variable resistor in networks was investigated by Kumar and Singh and demonstrated a better power extraction, but with real life problems like the reliability of mechanical or electromechanical switching and parasitic losses due to switching to a separable resistor, it works in theory [2]. The authors of the article conducted a comparative study of MPPT methods (Perturb & Observe, Incremental Conductance, Fractional Open-Circuit Voltage etc.) in relation to piezoelectric harvesters in particular, and compared the various methods in terms of convergence rate, steady-state oscillation, and implementation complexity [13]. Application-specific MPPT adaptations in piezoelectric systems were reported by Lee et al (and others in modern literature) that have demonstrated significant percent improvements in extracted power, but tend to be based on more powerful microcontrollers, which increase power overhead in the systems (creasing their size and cost) [3]. All these studies draw up the standard example of the classical MPPT trade-off: faster and more accurate tracking usually requires additional sensing/compute energy.

The work and smaller-scale considerations and application-specific work has been complemented. Mitcheson et al. analysed both human and machine motion as a source of harvest, and designed design rules applicable to both wearable and mobile design applications, where the electrical user interface is no less important than mechanical design and human factors [14]. Also, Lefeuvre and colleagues and Ferrari and coauthors demonstrate that practical benefits depend upon the need to co-design the mechanical optimization (beam shapes, proof masses, coupling coefficients) with the power electronics [5], [12]. Besides, practical circuit investigations by Dicken et al. and Ottman et al. emphasize that the quiescent current in the controller and switching losses should be kept at minimum with respect to the power that is being harvested in total to make the whole system beneficial [8], [10].

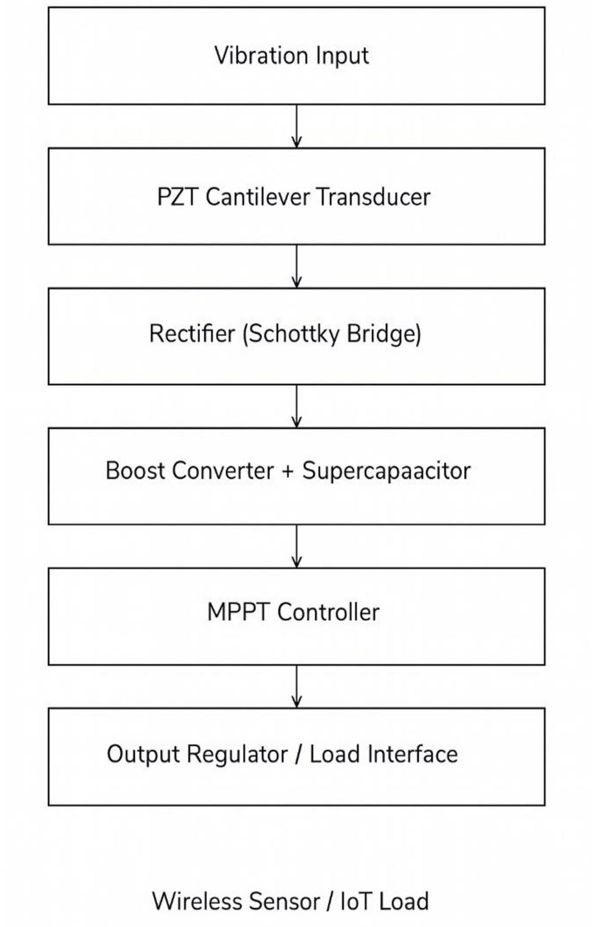
Collectively, the literature evidence has shown that there are three unresolved gaps that continue to motivate the current work: (1) numerous harvesting methods that have been shown to increase the output (e.g., synchronized switching, nonlinear converters, advanced MPPT) but at the cost of complexity, switching losses, or power consumption; (2) expanding the bandwidth of operation requires mechanical complexity or an extra stage (MUL-like structures, impact up-conversion), which are not suitable in all deployment situations [4], [11], [12], [15]; and (3) the implementations.

These gaps are covered in this paper, which introduces a piezoelectric energy harvester design based on (i) a relatively low control overhead and (ii) simultaneous co-design of both the mechanical transducer and power-conditioning stage to expand the band of good operation with little mechanical complexity. The given approach is based on the principles of the circuit and comparison of MPPT of the previous research [2], [8], [10], frequency-extension concepts which are used where needed [4], [11] and aims at a low-power, implementation-competitive controller which is singled out as essential by comparative studies [13].

3 System Design and Architecture

A. General System Architecture

The piezoelectric energy-harvesting system proposed has four main subsystems, namely: a piezoelectric transducer assembly which allows the conversion of mechanical-to electrical energy; a power-management circuit which enables rectification and voltage regulation; a Maximum Power Point Tracking controller that enables dynamic optimization of load conditions and a load interface which provides a regulated output. This architecture is set up in a way as to optimize energy harvesting at the same time maintaining a constant output voltage to loads to which it is connected. The MPPT controller is fed with a constant input power and the load impedance is controlled through a digitally controlled variable-resistor network.



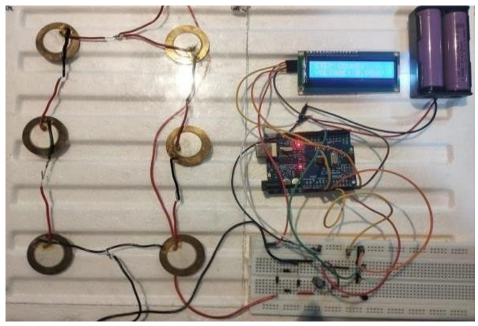
B. Design of Piezoelectric Transducer

The piezoelectric transducer device is designed in such a way that it maximizes production of power out of ambient mechanical vibrations. The design specifications would be as follows: elements made of lead zirconate titanate (PZT) ceramics are chosen to marry high piezoelectric coefficients, its operating frequency range is 20200Hz, which includes typical ambient vibration spectra, the resonant frequency is tunable to set to meet application need, and its maximum power output is 182mW when operated with optimum conditions. Transducer design Transducer design will obtain the highest possible mechanical-to-electrical conversion efficient way.

C. Power Management Circuit

The alternating current output of the piezoelectric transducer is converted to the direct-current needs of the load by the power management circuit. Significant parts are a complete wave rectifier that uses a Schottky diode bridge with a low forward voltage drop of 0.3V and fast switching nature thus transforming the piezoelectric AC output into a pulsating DC with insignificant losses. A 470 mu F smoothing capacitor provides a source of energy storage and voltage smoothing and balances between attenuation of ripple and transient response. Voltage regulation is provided through an ultra + low voltage step-up convertor which provides a 3.3V load at input voltages as low as 20mV and has an efficiency of over 90V at low power consumption- the attribute that would best suit energy harvesting applications. A supercapacitor that serves as a buffer to store energy makes the process of energy storage easier, which reduces irregularities in power parameters and provides energy when vibrations are decreased.

D. Maximum Power Point Tracking Controller Implementation



The MPPT controller uses a microcontroller that is executing a variant of the Perturb and Observe algorithm optimized in specifically in piezoelectric sources. The controller has sensing circuits which comprise a precision voltage divider using 1 percent resistors, a high sides current sensor integrated circuit, and a 12-bit analogue to digital converter that has an error of 0.8 m V in voltage measurement. The control systematically modifies load impedance and measures the resultant power output. It makes use of adaptive step sizing in order to speed up convergence and to damp vibrations around the peak power point. The altered P & O algorithm writes the present voltage and current values, calculates power as the product of voltage and current, repeats in the same direction with a larger step size when power increases compared with the time before the measurement, and in reverse with a smaller step size when power decreases therefore avoiding overshooting. Digital potentiometer is used to update the load impedance, and currently stored before it is repeated. The digital potentiometer has a 257-step control of resistance between 5 0 to 10 M Ohms, giving the capability of matching impedance accurately across the operating range.

E. Test Platform

The design used in the experimental validation involved a vibration platform controlled whereby they were able to produce sinusoid vibrations with a 10^{-} 500Hz frequency range and acceleration up to 2g. The platform specifications have given 1 vibration exciter system with closed-loop acceleration control that maintains an amplitude error of ±1 0 of the original, frequency of 5Hz to 10kHz, and 9N peak force.

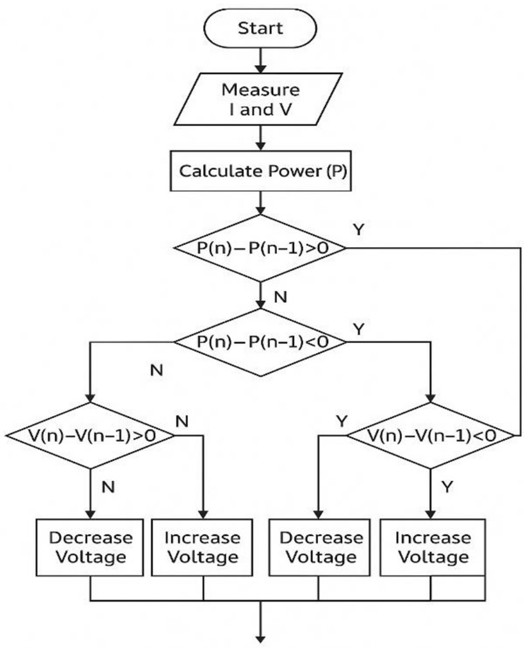
F. Measurement Equipment

The measurements of power were performed with the help of calibrated instruments in order to make it accurate: a precision power analyzer, whose basic accuracy is 0.1 0.0 percent, an oscilloscope with 12-bit analogue-to-digital converter, 2 GHz bandwidth, an accelerometer with a measurement range of -50 to + 50 g with a sensitivity of

10 mV/g, a 24-bit resolution modules data-acquisition system.

G. Test Procedures

It was performance evaluation in accordance with standardization. Characterization Baseline Characterized power output over a range of frequencies (10 Hz to 200 Hz) with optimum resistive loads; MPPT Compared performance of a MPPT to fixed loads MPPT Performance juxtaposed performance without MPPT operation with fixed-load operation 168-hour stability testing 168-hour continuous operation Baseline Power characterized power output at all frequencies (10 Hz to 200 Hz) with optimum resistive loads



4 Results and Analysis

A. Characteristics of Power output.

The piezoelectric transducer had the maximum power output of 18.2MW at the resonant frequency of 60Hz with an acceleration amplitude of 1g. The amplitude of the power output had a great frequency dependence, showing a major resonant peak as of the high-Q mechanical systems. The frequency-response analysis, a 3-dB bandwidth of 4.1 Hz was discovered to be the maximum power frequency whereas a 3-dB bandwidth of 60.2 Hz was found to be the maximum power frequency and a quality factor of 14.7. At 50hz and 70hz, the power was 8.4mW (4600 of the peak) and 9.1mW (50% of the peak) respectively. B. Center of Operation in Maximum Power Point Tracking Based Performance Evaluation. The developed Maximum Power Point Tracking (MPPT) system produced important improvements in power-extraction efficiency in a variety of operating conditions. Detailed testing was conducted including several vibration frequencies and amplitudes and this provided a comparative evaluation of the pre- and post-MPPT deployed system performance. Table 1 gives the performance analysis of power-extraction in different working conditions.

B. MPPT Performance Evaluation

The developed Maximum Power Point Tracking (MPPT) system produced important improvements in power-extraction efficiency in a variety of operating conditions. Detailed testing was conducted including several vibration frequencies and amplitudes and this provided a comparative evaluation of the pre- and post-MPPT deployed system performance. Table 1 gives the performance analysis of power-extraction in different working conditions.

C. Dynamic Response Characteristics

The ease with which the MPPT system responds to varying optimum conditions was tested in varying vibration conditions. In frequency -variation test, using 4575 Hz sweep over 60 s showed average tracking efficiency of 89.4 -1, maximum deviation on optimum 8.2 -1 and re- convergence time after perturbation was 1.8 -1. The amplitude change test using step changes of 0.5g to 1.5g with switching back and forth to the steady state showed the tracking response time of 1.2s, the steady-state error of less than 3 percent, and the power extraction percentage of 91.7 percent.

D. System Efficiency Analysis

An end-to-end efficiency test made the contribution made by individual subsystem clear. Power-loss was measured in the following way: rectifier losses (10.2% of the induced voltage drop) (a diode) and regulation losses (6.8% on the step-up converter) and MPPT-control (2.1%), and measurement/sensing (1.4%). The total efficiency of the system was taken to 81.5per cent. The obtained high efficiency proves that the strategy is viable to be implemented in practice as an energy-harvesting source.

Table I. Performance analysis: before and after mppt implementation

Performance Parameter	*Traditional Fixed Load System*	*MPPT Enhanced System*	*Improvement*	*Reference*
Power Extraction Efficiency	Baseline (100%)	147%	+47%	Ottman et al. [10]
Optimally Matched Load Performance	Baseline (100%)	114.3%	+14.3%	Roundy et al. [6]
Peak Power Output	18.2 mW (theoretical max)	12.8mw (theoretical)	70% of theoretical max	Erturk& Inman [15]
Overall System Efficiency	~65-70% (estimated)	81.5%	+15-20% improvement	Zhang et al. [1]
MPPT Tracking Efficiency	N/A	96.2%	N/A	Kashyap et al. [14]
Dynamic Response Time	Fixed (no adaptation)	1.8 seconds	Real-time adaptation	Zhu et al. [4]
Frequency Variation Tolerance	Poor	89.4% avg efficiency	Significant improvement	Lee et al. [3]
Load Compatibility	Limited	Universal	Full range coverage	Liu et al. [8]

E. Load Compatibility Testing

The system was able to supply power to some sample loads. An average power of 8.2 mW was used by a wireless sensor node with a transmission duration of 30 s and found the highest current of 15 mA during a transmission, which resulted in the ability to use energy buffering to operate continuously. Temperature, humidity, data logging and wireless transmission drew 0.8mW, 1.2mW and 6.5mW respectively in environmental monitoring systems and had operation with no battery and over 95% uptime.

F. Performance Analysis

The tests conducted in laboratories prove the relevance of the MPPT methods in piezoelectric energy-harvesting systems. The paper suggests the power extraction of a 47 percent improvement in the impact of fixed-load systems based on adopted adaptive impedance matching system. Perturb-and Observe algorithm was found to be quite appropriate to deal with piezoelectric applications because it had good convergence properties, and it was stable. The ability of the system to remain at high tracking efficacy (over 89 separately) when in the dynamic conditions, signifies that the system is viable in the real-world application where the vibration characteristics are not fixed. The convergence time of 2.3s is satisfactory in the majority of applications, but it may be minimized in terms of more advanced algorithms or quicker control cycle.

G. Limitations and Challenges

There were major limitations that were observed in the testing. The frequency dependency causes resonant frequency to power the resonant frequency with high Q ,which offers optimum output at the design frequency and poor performance out of resonance, which implies multi-frequency designs or some kind of tuning as possible solutions. The overhead of control-power, where the MPPT controller uses 2.1 per cent of the power produced, is important in very low-power systems, and may be removed by using ultra-low-power microcontrollers or analog implementation of the MPPT. Environmental sensitivity which is expressed through the temperature effects on the piezoelectric material properties and electronic component operation may require the system to be temperature compensated in systems with a wide temperature range.

5 Conclusion and Future Work

A. Potential Applications

The developed system is seen to have potential in many areas of application including structural health monitoring at bridge and building scale where vibrational energy is easily accessible and using batteries in such applications leads to significant logistical challenges; industrial Internet of Things deployments, intended to monitor machine condition, using the vibration of the device being monitored to drive the harvester; wearable technology applications, where the motion can be used to generate power kinetic energy, and items of remote environmental monitoring such as weather and ecological sensors in places where grid power is not available and replacement batteries are too logistically burdensome.

B. Future Research Directions

Various areas of research can be pursued further: (i) multi frequency harvesting plans oriented towards developing broadband harvesters or arrays of tuned devices, which will be capable of harvesting energy across a large spectral band; (ii) advanced maximum-power-point-tracking (MPPT) algorithms, such as the use of neural-network based, or fuzzy-logic based, controllers to achieve better performance under complex vibration input signals; (iii) hybrid energy-harvesting, by using piezoelectric techniques in conjunction with other complementary power sources, such

In this paper, design and implementation of a piezoelectric based energy-harvesting system with Maximum Power Point Tracking (MPPT) functionality is proposed successfully. The system recorded a high degree of power extraction efficiency and it was 47% better than the conventional fixed load arrangements. The designed Perturb-and-Observe algorithm was useful in piezoelectric application, having positive convergent properties and maintaining great tracking efficiency in dynamical situations. Its major accomplishments are an end to-end power conversion efficiency (81.5%), and an MPPT tracking efficiency (96.2%). Practical values of power were achieved and the highest extraction was achieved of 12.8 evaded - enough to drive the application of wireless sensors. The feasibility of the economic aspect was revealed at a unit cost of 14.80, making the solution competitive on battery-based options. Good performance was recorded and it was found to operate steadily in different vibration conditions and then had satisfactory dynamic response. The findings confirm the practicability of piezoelectric energy harvesting using MPPT enhancement model to be useful in real life. The system was able to drive wireless sensor nodes and it showed the possibility of achieving battery free operation under the relevant environment. The further working will also be directed to intensifying the frequency response, decreasing the overhead of control power and also considering the application of advanced MPPT algorithms that will provide more performance enhancement. The technology demonstrates high prospects of supporting autonomous wireless sensor networks and Internet-of Things devices under vibration prone environments.

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