DEVELOPMENT OF NEW PIEZOELECTRIC GENERATOR WITH OPTIMUM POWER FLOW FOR ENERGY HARVESTING

SYNOPSIS OF THE THESIS

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By

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Abstract

Ambient vibration based energy harvesting using piezoelectric harvester has been of great interest for researchers for low power wireless, remote and embedded applications. In this work a novel polyvinylidene fluoride (PVDF) based nanocomposite with enhanced piezoelectric property has been developed in laboratory by synthesizing PVDF with multi walled carbon nanotubes (MWCNT) for ambient vibration energy harvesting. The piezoelectric properties of the composite have been optimized by adjusting composition of MWCNTs in PVDF and tuning different process parameters. The PVDF-MWCNT composite thin films with cantilever structure is then tested on vibration source for energy harvesting and compared with base PVDF material films. The parameters like material composition, baking temperature, spinning speed, poling voltage on composite are adjusted to optimize piezoelectric properties of material. FTIR, XRD, scanning electron microscope (SEM) analysis and ferroelectric measurement results confirms better piezoelectric properties in new PVDF-MWCNT composite. Measurement of Parameters like charge constant, dielectric constant, young's modulus and coupling coefficient shows reasonable good improvement in PVDF-MWCNT composite. The new composite film generates 2 to 2.5 time's higher voltage than pure PVDF film. Further, for optimizing power flow in load circuit, different kinds of energy harvesting circuit topologies have been studied, analysed and compared. Then a modified self tuned non linear energy harvesting circuit with adaptive control has been proposed. The circuit provides set value of output voltage using feedback control of the duty cycle of the switching device. The intended circuit harvests energy 1.5 times higher than conventional bridge circuit. Energy harvesting module with novel composite and self tuned circuit shows overall gain of 3.5 in the extracted energy. Further, an analytical expression for electromechanical model has been derived and a new simulation model called Mechatronic model using Matlab Simulink is proposed. The simulation model is validated with experimental results.It is also compared with equivalent electrical model used in past research works.It has been found that novel mechatronic model gives results proximate to experimental results as compared to electrical equivalent model. The mechatronic simulation model has proved to be a very useful tool for study and analysis of behaviour of different kinds of piezoelectric material for energy harvesting purpose.

State of the Art of the Research Topic

The idea of Low power energy harvesting using piezoelectric materials has been studied by many researchers in the past few decades. The PVDF polymer is gaining popularity as a potential piezoelectric material for ambient energy harvesting. Though energy harvested is of hundreds of micro to few milli watts, it is a good aspirant of self powered applications such as powering wireless nodes, embedded electronics, biomedical imagining, remote sensing, body implants, RFID, robotics, industrial automation, structural health monitoring, healthcare, agriculture, civil and defence. The biggest advantage of such ambient energy harvester is that it can eliminate use of batteries which has the biggest constraint of limited life and frequent maintenance. Among different kinds of piezoelectric material PVDF as an energy harvesting material has several advantages over piezoceramics such as high tensile strength, high elastic compliance, good dynamic response, flexible, and low acoustic impedance which makes it suitable for ambient vibration energy harvesting[14]. But the problem with PVDF is that it has lower electromechanical coupling coefficient and lower strain constant as compared to piezoceramics which results in reduced efficiency of the harvester. In one of the early study of power harvesting to extract energy from the expansion and contraction of the rib cage while breathing, a prototype for power harvesting using polyvinylidene fluoride (PVDF) film was employed in vivo on a mongrel dog. The prototype produced maximum voltage of 18V, with power of about 17μW [39]. The effect of piezoelectric material properties were studied, it has been found that the higher output is associated with higher piezoelectric strain constant, piezoelectric stress constant, elastic compliance and the relative dielectric constant, and to other associated material properties called the figure of merit and the coupling coefficient. To improvise typical piezoelectric parameters of PVDF some researchers have tried with different combinations of PVDF with other materials or mixing with piezoceramics for enhancing amount of energy harvested. But mixing of polymer and ceramics is complicated process and faces challenges of homogeneous material structure.

For industrial applications to improve mechanical a physical properties of PVDF researchers have experimented with preparing PVDF and CNT composites. CNTs have gained interest as nano materials due to their exceptionally outstanding properties like extremely high Young's modulus around 1 Tpa. and ultimate tensile strength 10-200GPa, high electric and thermal conductivity. CNTs as lightweight, highly elastic, and very strong composite fillers [10]. In one of the studies CNT reinforced PVDF powders had been produced. The mechanical performance of the nanocomposite powder containing 2.5 wt.-% CNT increased the tensile modulus, tensile strength, and strain to as compared to PVDF[5,8]. It was demonstrated that the nanotube-based polymer samples had improved sensing performance as compared to pure PVDF samples, which was due to increased Young's modulus of elasticity of the composite[9,10].Inclusion of CNTs in PVDF affects dielectric strength of composite. Particularly at low frequencies dielectric properties of MWCNT/PVDF composite increasing MWCNT content up to 1.6% volume dielectric constant increases significantly and above 1.6% of volume dielectric loss increases rapidly and approaches percolation[11].Copolymer based SWNT/P(VDF-TrFE) composites demonstrated higher dielectric constants and ferroelectricity depending on the weight fraction of CNT under the same polling voltage [6]. The ferroelectric measurements proved that the energy density of CNT–COOH, -OH loaded PVDF films were increased two to three time as compare to the pure PVDF films [1].Thus past researchers have worked on PVDF, PVDF copolymers combined with CNT to improve mechanical strength for industrial applications and few of them have done ferroelectric studies to test the effect of inclusion of % weight of CNTs on piezoelectric properties of the composites.

A mathematical model was developed with simplified design procedure required for determining the appropriate size and vibration levels necessary for sufficient energy to be produced and supplied to the electronic devices[19]. A distributed parameter mathematical model for cantilevered piezoelectric harvesters was derived based on Euler–Bernoulli beam theory. Effect of geometry of harvester, damping, strain nodes and coupling coefficient were studied [26, 29]. The equivalent circuit model considering multiple modes of the system was established and simulated in the SPICE software. The parameters used in the equivalent circuit model were identified by Finite Element Analysis, according to different mechanical conditions[30].The analytical approach based on Euler–Bernoulli beam theory and Timoshenko beam equations for the voltage and power generation, and a matlab simulation model with ac-dc rectifier was used to compared the electrical equivalent circuit and energy method[20,23].

The improvement of energy generation and storage methods combined with the decreasing power requirements of today's electronics help bring the concept of creating self-powered electronics[31]closer to reality. In [17] a PWM controller with a DC–DC step-down converter, used with calculated optimal duty cycle for maximum power. But as circuit used which consumed a significant amount of power. So in modification [18] control circuitry was removed and a pulse-charging circuitry was added. This circuit was found to provide a 325% increase in power. Power optimization with the Standard interface, requires an impedance adaptation of the terminal electric load. This problem was solved with the new SCE i.e., Synchronized Charge Extraction technique. Moreover, this technique increased the harvested power by a factor 4.Two others power optimization techniques, known as Synchronized switch harvesting on inductor (Parallel-SSHI and Series-SSHI), were suggested harvested in weakly coupled systems or non-resonant systems.[34,35] The simulation model results depicted that use of the parallel inductor synchronized switch energy harvesting circuit increases power transfer by over 400% as compared to standard circuit is used. [32] The optimal resistive load was estimated to maximize the power output. Different capacitive loads are tested to store the output energy. [36] The SSHI circuits require tip displacement be monitored, whereas pulsed resonant converter, PRC based control circuit works in the electrical domain. It was demonstrated that the PRC gave better power output when the factor $\omega\tau$ is sufficiently large. [38]

A majority of the past researches were focused on enhancing efficiency of piezoelectric devices by modifying physical and geometrical construction, as well circuitry and energy removal methods. The challenge faced by researchers was gap between the energy consumption of the circuits used to store the harvested energy and the power generation capacity of the harvesting system. Further all these methods are not suitable for low frequencies available in machineries, structures and walking and Sometimes inductor size required in circuits made them impractical to employ.

Problem Definition

The drawback of wireless and remote applications is dependency on battery supply. One of the solution is to make such applications self sufficient by acquiring energy from environment. Energy levels available in ambient vibrations can be effectively converted in electricity and used to supply such wireless and remote applications. PVDF polymer has several advantages of high tensile strength, high elastic compliance, good dynamic response, flexible hence, can be fabricated in any shape, and low acoustic impedance which is close to water, human tissue and adhesives which makes it suitable to be attached or embedded anywhere. But it has constraint of lower piezoelectric output as compared to piezoceramics for same amount of input energy for given size.

The challenge is to make PVDF material more sensitive to input vibrations available and to enhance its capability to convert this vibration energy into electricity. As the size and geometry may be application dependent, major improvement is required in material's piezoelectric properties.

To supply wireless nodes dedicated interfacing circuits are required which plays crucial role in energy harvesting. The piezoelectric output of harvester may be fluctuating depending upon varying condition of vibration levels. For a particular vibration source there may be set boundary limits of frequency and amplitude, though the output may be intermittent if vibration level is too low. Further circuit needs protection against high voltage generated from high vibration input levels,which may reduce reliability of the energy harvesting system.

Hence, to ensure uninterrupted power flow in load circuit with set value of voltage the interfacing circuit needs have self adjusting property as well minimum internal loss for optimum power flow.

To estimate output power electrical equivalent simulation model had been used in past works. But some of the parameters could not be incorporated easily in electrical model. Electromechanical coupling and mechanical damping effect of the harvester structure are crucial factors which have great impact on output of piezoelectric harvester.

Hence, to study general behaviour, to distinguish effect of such parameters and other variables and to estimate power output under varying input and load conditions, we need to design and calibrate an simulation model which can incorporate, a) All mechanical input source characteristics, b) A piezoelectric element with its material properties, geometry and size and c) An electrical interfacing circuit with adaptive control for power transfer to the load.

Majority of past work are reported in either of the three above stated areas and all problems are not addressed together. Further, electrical equivalent model used lack flexibility to adjust all parameters of the above said three areas and needs many calculations to set input parameters.

Objectives and scope of work

1. To develop a CNT reinforced composite to improve piezoelectric response of PVDF polymer based harvester.
2. To optimize power flow in load circuit by designing a converter this operates over a range of ambient vibration frequency levels.
3. To develop a simulation model of piezoelectric generator for energy harvesting from ambient vibration sources that reflects general behaviour and response of energy harvester module for low power remote and wireless applications.
4. To prepare a prototype of energy harvesting module and to compare simulations results for validation.

Scope of work

-To study characteristics of different kinds of additive materials that can be reinforced with PVDF material for enhancing piezoelectric response of PVDF material.

-Compare and analyze different additives to check suitability for synthesis with PVDF.

-Developing new composite material in laboratory and to optimize piezoelectric properties of the composite.

- To study and compare different types of power extraction techniques to decide appropriate energy harvesting circuit design.

-Optimizing power flow in load circuit by designing proper controller circuit.

-Testing of piezoelectric generator module for ambient vibration energy harvesting.

-To develop a simulation model which can eliminate drawbacks of electrical equivalent simulation model.

Original contribution by thesis.

This work identifies that inclusion of CNT in PVDF material not only improves tensile strength and modulus of elasticity, but it also improves β phase content in PVDF matrix. As in β phase, material exhibits good piezoelectric behaviour. In this work a novel PVDF and MWCNT composite with enhanced piezoelectric properties for energy harvesting purpose has been developed in our laboratory. We have optimized the piezoelectric properties of composite by adjusting the percentage of MWCNT content in PVDF and by tuning different process parameters like solvents type, spinning speed, baking temperature which also affects piezoelectric nature of the material up to a certain extent.

As energy harvested from ambient vibrations is of low level, a highly efficient interfacing circuit is needed for optimizing power flow in load circuit. Different techniques used for non linear energy harvesting has been compared and analysed to decide appropriate circuit topology. In this work, for harvesting energy from ambient vibrations available in the environment, a self tuned controller circuit has been designed for optimizing power flow into the load circuit with adaptive algorithm. The intended circuit transfers power at a higher rate than conventional bridge circuit.

A test structure for vibration energy harvesting has been fabricated in our laboratory. Energy harvesting module has been tested for different vibration frequencies, input force and load conditions. The harvester has been tested successfully for low frequency range.

An analytical expression for power output of the harvester has been derived and a novel mechatronic simulation model has been developed using simulink to study general behaviour, characteristics and estimate output of different kinds of piezoelectric material. The model is compared with electrical equivalent simulation model. The results of the research work confirm that mechatronic model creates more realistic picture of piezoelectric behaviour of the material. Simulation results are also compared with hardware results. The proposed simulation model gives proximate results to the hardware results.

Methodology of research, results/comparison

This work is divided in three major sections.

A. Optimization of Piezoelectric properties of PVDF-MWCNT based composite.

B. Optimization of Power flow by introducing appropriate energy harvesting circuit.

C. Development of a mechatronic simulation model for the study of behaviour of different kinds of piezoelectric materials for energy harvesting.

A. Optimization of Piezoelectric properties of PVDF-MWCNT based composite.

The PVDF- MWNT samples are prepared with different composition of functionalized MWCNTs in PVDF Solution. The solutions with different mass ratios of (THF:DMF)for PVDF film and with different concentration of PVDF and MWCNT-COOH for composites are drop casted on a glass substrates and spin coated at different speed and then dried in a vacuum oven. The experiments have been done by varying different process parameters like effect of material composition, type and concentration of CNT, ratio of solvents, spin speed, baking temperature, poling voltage and mechanical parameters. Effects of these parameters are studied in relation to piezoelectric behaviour of material analyzed and process parameters are tuned accordingly to optimize piezoelectric properties of the proposed PVDF-MWCNT composite. Finally, the thin films of thickness~ 25 μm on glass substrate are produced. Samples are polled under high electric field for further enhancement of β phase content.

From experiments it has been observed that crystalline behaviour and β phase orientation increases with increase in %wt of MWCNT (COOH),but as the ratio is to be limited to percolation threshold and to maintain dielectric nature of the composite it is adjusted to 0.08%wt as optimum. We observed that at lower frequencies, the dielectric loss increases with increasing concentration of MWCNTs upto 0.08%wt.Whereas sudden decrease in dielectric loss is observed at higher concentration (0.1%wt). Increase in spinning speed increases stretching of film due to centrifugal force which stretches molecular chain and in turn results in increased β phase orientation. But at higher speed above 3000 rpm, there is decrement in β phase in the films due to permanent damage of molecular chains due to large centrifugal force. Further, higher spinning speed decreases the thickness of the film and causes crack formation. Hence, spinning speed of 2500 rpm is preferred for film making. Baking temperature plays an important role in crystallization composite film. Morphological study by SEM analysis shows that film at 90°C and 120°C are less porous and surfaces are smooth as compared to films baked at lower temperature. It is also found that film prepared at room temperature are brittle and fails to test. FTIR spectra shows highest β phase formation at 90°C ($2\theta= 20.6^o$) and at higher temperature β phase is suppressed and α phase found to be more prominent. The films baked at 90°C is less porous and has higher β phase content then film baked at 60°C .Morphology from SEM images of outer surface of PVDF and PVDF/MWCNT-COOH are shown in Fig:1(a) and (b) at which illustrates homogenous dispersion of MWCNTs in PVDF matrix. The crystalline behaviour of the films are analysed with X-ray diffraction (XRD) and FTIR study. The XRD data is taken in the scan range (2θ) of 15° -26° at room temperature. Peak for composite is observed at 20.6^o and FTIR result shows peak at 1276 cm^{-1} which confirms β phase formation as shown in Fig: 1 (c) and (d). Results from XRD data confirms that increase in poling voltage increases β phase orientation in composite. But the poling voltage is to be limited to breakdown strength of the composite. Further, it is difficult to apply high electric fields to PVDF film fabricated in the laboratory due to problem related to film texture, surface impurities, pinholes and chances of cracking. For 1000V, hysteresis loop is very steep. With an increase in applied voltage, the area and symmetry of the loop increases which shows increase in the polarization of the composite. The enhancement of polarization in the composites films implies the increase of polar β-phase of PVDF. Further, increase in MWCNT concentration (0.02% to 0.08%) the value of remnant polarization Pr and area of P-E loop increases noticeably. PE curves are plotted for pure PVDF, 0.05%wt and 0.01%wt concentration of MWCNT as shown in Fig:2.the dielectric properties, the relative permittivity (ε_r) and the loss factor were determined as a function of frequency. Graph for permittivity (ε_r) vs. frequency is plotted for lower frequency region. It is observed PVDF-MWCNT (0.08%) composite has higher permittivity of 75 as compared other concentration of MWCNT. The dielectric constant also depends on the material's polarization, the higher the polarization of the particles, the higher is dielectric constant. At an electric field of 1500 volts, composites show near rectangular hysteresis loops that indicate the reversal of the polarization. It has been observed that the area of each loop is proportional to the concentration of MWCNT in the composite. At higher level of applied voltage better rectangular hysteresis loop can be obtained but 1500 volt electric field is also challenging to apply to specimens. Based on all these facts and outcomes of PE loops, the poling voltages of each film is restricted to 1500 V.From ferroelectric P-E loop study, the area under the curves gives the charge storage of the pure, and composites films. This clearly shows that only very little amount (0.08 %wt) loading of functionalized MWCNT enhances the energy density of composite film. At

0.08%wt the charge constant d_{31} shows improvement from 23 to 62 pC/N. coupling factor from 12 to 23.

Table: 1 Dielectric constant and remnant polarization at applied voltage of 1500V

Concentration(%wt) of MWCNT	0	0.02	0.05	0.08
Dielectric constant	12	13.9	15.7	16.1
Remnant Polarization mC/m2	17	15.1	24.8	28.5
Coercive field MV/m	19	33.4	35.6	42

Table: 2 Generated open circuit voltage at different vibration level.

Frequency of vibration	5Hz	25Hz	50Hz	80Hz
V_pvdf (volts)	0.85	7.2	15.3	30.1
V_pvdf-cnt (0.08%wt)(volts)	1.8	16.3	37.2	74.3

Table: 3 Mechanical properties of PVDF-MWCNT

Concentration(wt%) of MWCNT	0	0.02	0.05	0.08
Max stress (MPa)	40	41	43	45
Young's modulus (MPa)	1410	1560	1894	2075

The generated voltage is the function of d_{31} also increases with increase in MWCNT concentration as shown in Table:2. Study of Stress-strain curves for PVDF and PVDF/MWCNT reveals that inclusion of MWCNT in PVDF increases the mechanical strength. The tensile strength and Young's modulus are shown in Table 3. The tensile strength and Young's modulus of PVDF/MWCNT nanocomposites are much better than those of pure PVDF. The significant rise in Young's modulus and tensile strength of PVDF clearly confirm the effect of the MWCNT in the PVDF/MWCNT composites.

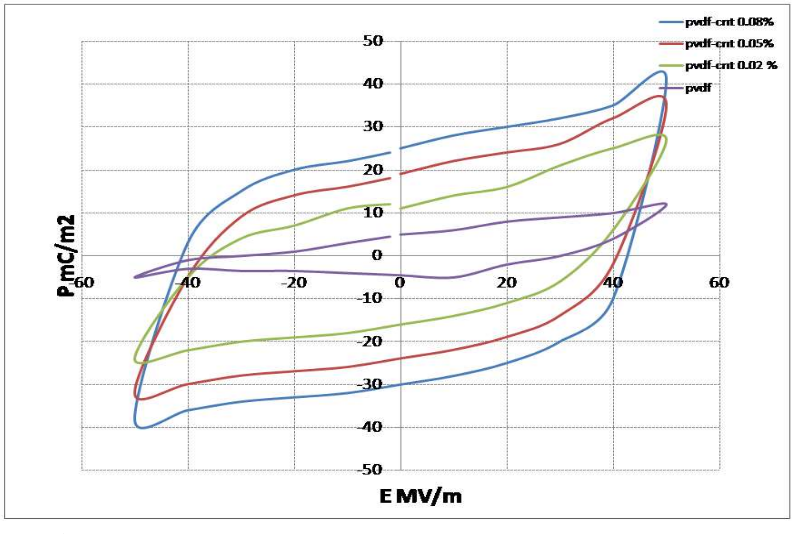


Fig:2 PE loops for pure PVDF, PVDF-CNT (0.02%wt, 0.05%wt, 0.08%wt)

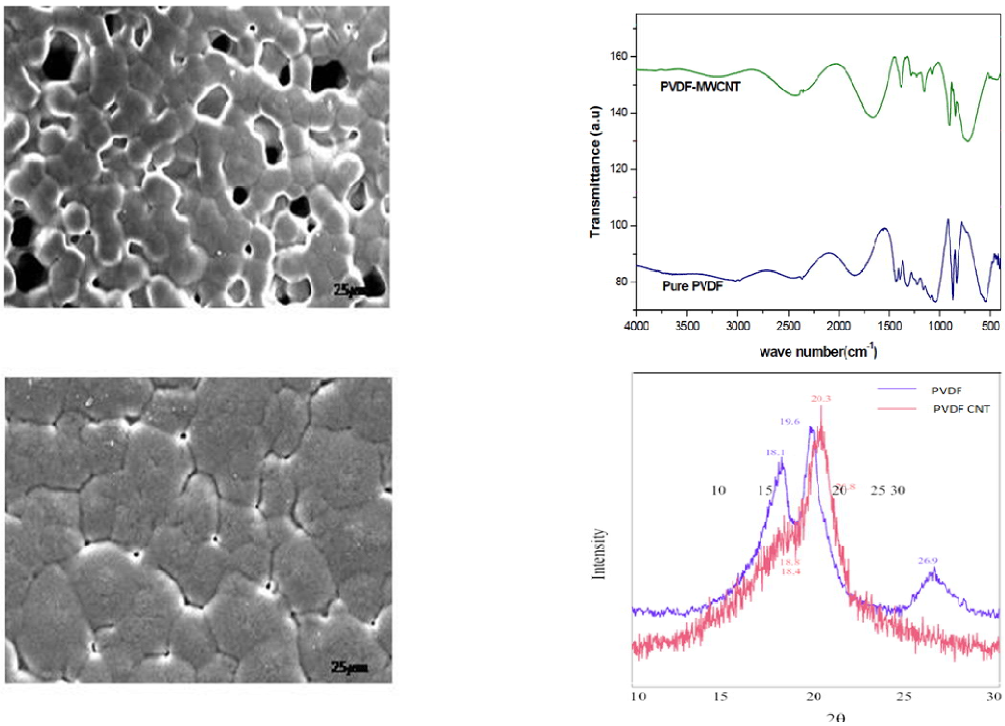


Fig.1. (a) SEM images at 60^{o}c (b) SEM images at 90^{o}c (c) FTIR of PVDF, PVDF-CNT (0.08%wt) and (d) XRD of β PVDF and composite PVDF-CNT (0.08%wt)

B. Optimization of Power flow by introducing appropriate energy harvesting circuit.

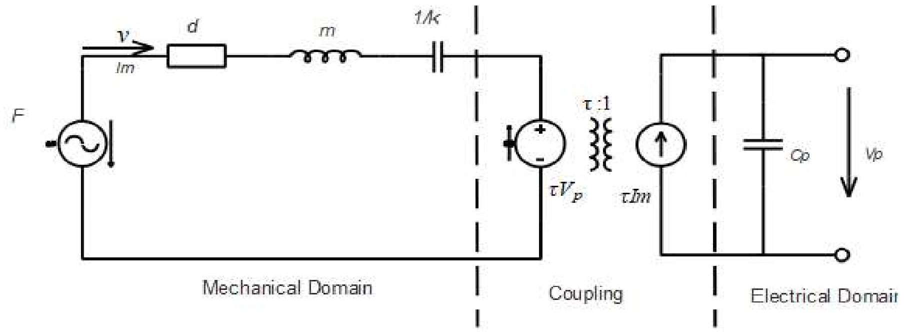


Fig: 3 Equivalent circuit of coupled dynamic system of piezoelectric harvester

When the piezoelectric material is operated in 31 modes, the stress is applied along the x axis, whereas the voltage appears in the z axis.

Energy balance equation will be

$$\int ma\dot{Z}dt = \frac{1}{2}m\dot{Z}^2 + \int d\dot{Z}^2\,dt + \frac{1}{2}kZ^2 + \int \tau V_p\dot{Z}\,dt \qquad (1)$$

Total energy=kinetic energy+ mechanical damping loss + elastic energy+ electrical energy

Where, Electrical energy=energy stored in piezo capacitance + Actual energy harvested

$$\int \tau V_p\dot{Z}\,dt = \frac{1}{2}C_pV_p^2 + \int V_p\,Idt \qquad (2)$$

Piezoelectric Output voltage and output power and maximum power will be

$$V_p = \frac{Fl\ _p d_{31}}{2\varepsilon I} \tag{3}$$

$$\mathrm{P}_{(\omega)} = \frac{\mathrm{m}\left(\frac{\omega}{\omega_\mathrm{n}}\right)^3 \omega^3 \mathrm{Y_m}^2 \zeta_\mathrm{e}}{\sqrt{\left[1-\left(\frac{\omega}{\omega_\mathrm{n}}\right)^2\right]^2 + \left[2(\zeta_\mathrm{d}+\zeta_\mathrm{e})\frac{\omega}{\omega_\mathrm{n}}\right]^2}} \tag{4}$$

$$\mathrm{P_{max}} = \frac{\mathrm{m}\omega_\mathrm{n}{}^3 \mathrm{Y_m}^2}{16\ _\mathrm{d}} \quad \text{Or} \quad \mathrm{P_{max}} = \frac{\mathrm{ma_m}^2}{8\mathrm{d}} \qquad \text{at } \omega = \omega_{\mathrm{n}} \text{ and } \zeta_\mathrm{d} = \zeta_\mathrm{e} \tag{5}$$

And corresponding electrical output will be

$$P_{max} = \frac{\left(\frac{0.5V_{mc}}{\sqrt{2}}\right)^2}{R_{mc}} \quad \text{and } \mathrm{V_{mc}} = \mathrm{ma}/\tau \tag{6}$$

Energy harvesting circuit plays crucial role in harvester module. Its performance affects efficiency of the harvester. For optimizing power flow in load circuit. A modified self tuned non linear energy harvesting circuit with adaptive control has been proposed. The circuit consists of a low-loss bridge rectifier and a competent buck converter. A step down chopper is used for voltage regulation which switches the current on and off with respect to the varying voltage to regulate the output voltage. The circuit provides set value of output voltage using feedback control of the duty cycle of the switching device. The buck converter changes the switching frequency according to the current flowing in load. Any change in load current causes the device to compensate it by adjusting the frequency at which it turns regulation on and off. The buck chopper utilizes pulsed power switching to maintain the output voltage. When the input voltage falls below the under voltage lockout threshold value, the converter shuts down. During this time, the output capacitor supplies the load till it gets discharged. The NMOS plays important role in making circuit energy efficient by reducing conduction loss. If the PMOS becomes on when the sleep comparator turns on, the NMOS turns and brings the current down to zero. The intended circuit harvests energy 3.5 times higher than simple bridge rectifier circuit. The schematic of proposed energy harvesting circuit is shown in Fig:4. Measured results in Table:4 confirms PVDF-MWCNT composite along with self tuned harvesting circuit generates more power as compared to base PVDF Harvester.

Table: 4 Output powers of PVDF and PVDF-MWCNT at different load resistances.

Load resistance (Ω)	100	500	1000	2000
PVDF power (mW)	65	12.8	6.2	3.2
PVDF-MWCNT(mW)	91	23.2	11	5.2

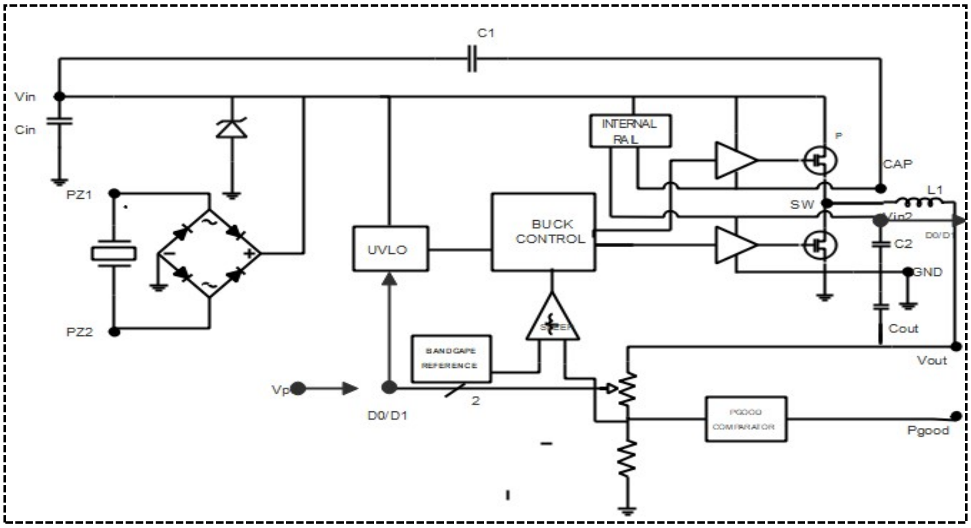


Fig: 4 Energy Harvesting Circuit

C. Development of new Mechatronic simulation model for the study of behaviour of different kinds of piezoelectric materials for energy harvesting.

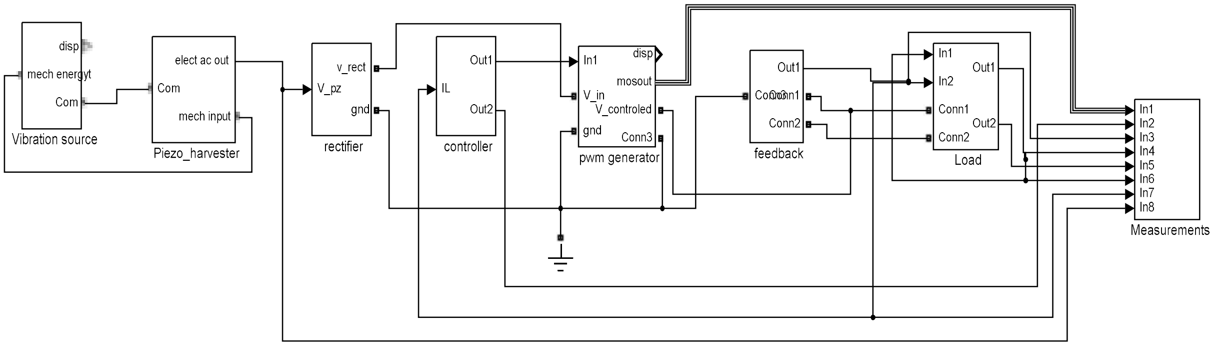


Fig: 5 Mechatronic Energy harvesting model in simulink

PVDF and composite material Values of voltage and power generated by mechatronic model are quite proximate to hardware result. Whereas voltage generated with electrical model differs more with actual harvester's result. This is due to lake of flexibility for setting individual mechanical vibration input parameters and piezoelectric material properties and size. Further it requires mathematical calculations for setting equivalent source input parameters. The testing is also performed for different frequency of vibrations ranging from 20 Hz to 100 Hz with different amplitude and load. Every time mechatronic model showed consistent behaviour and provided better result as compared to electrical model. The mechatronic model gives better result as it can imitate actual environment of harvester's condition due to following reasons,

1. Piezoelectric properties of the material can be incorporated and varied.

2. Loss due to electromechanical coupling effect can be predicted.

3. Effect of mechanical damping can be reflected, which plays very crucial role in energy harvester's performance.

4. Effect of change in individual parameter can be identified or discriminated.

5. Piezo element dimensions can be changed.

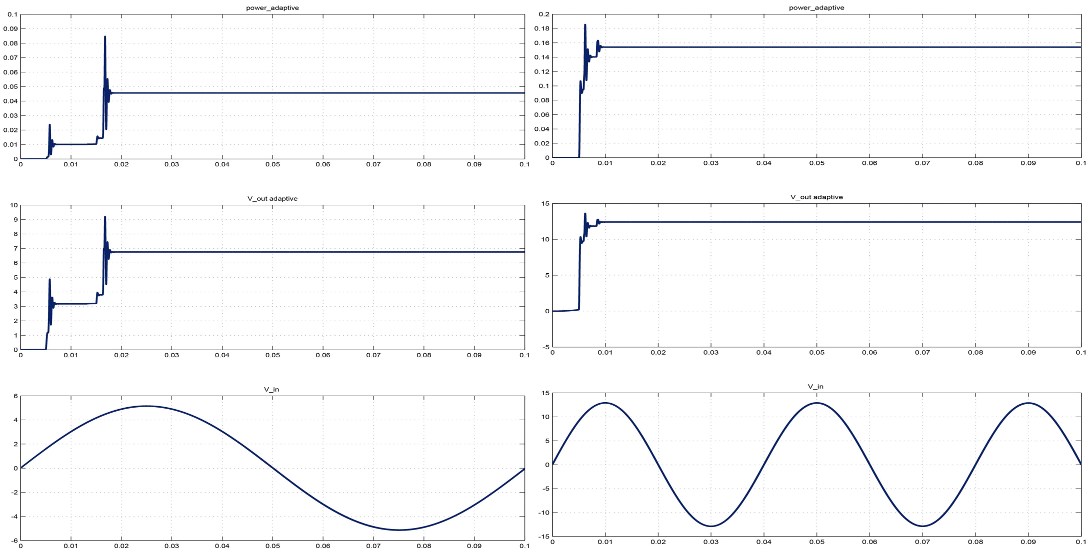


Fig: 6 Sample input voltage, output voltage and power at 10 Hz and 25hz with Mechatronic model.

Experimental Setup

Fig.7 shows block diagram of test set up of harvester model consisting of a scientific laboratory Oscilloscope, Scientific Function generator, Amplifier, Vibration generator, controller circuit and load resistance. Fig:8(a) shows lab experiment with piezoelectric element clamped to vibration generator. The vibrations produced in piezoelectric element have been measured using accelerometer and CRO. Composite material harvesting element is shown in inset. Fig:8(b) and (c) shows testing on a mechanical vibrating structure. The results confirm that PVDF-MWCNT composite generates more output voltage as compared to PVDF Film. Testing has been done for different input force and low level frequencies and results plotted are shown in Fig:9(a) and(b). which confirms that PVDF-MWCNT composite generates more output voltage as compared to PVDF Film for same vibration frequency. For different load conditions output power of PVDF-MWCNT with PVDF harvester with self tuned controller are plotted in Fig:10(a) and Power vs. Output Voltage plots of simulation and test results of PVDF-MWCNT and PVDF harvester with self tuned controller are plotted in Fig:10(b).Both plots confirms that PVDF-MWVNT harvester with self tuned circuit outperforms PVDF base harvester module.

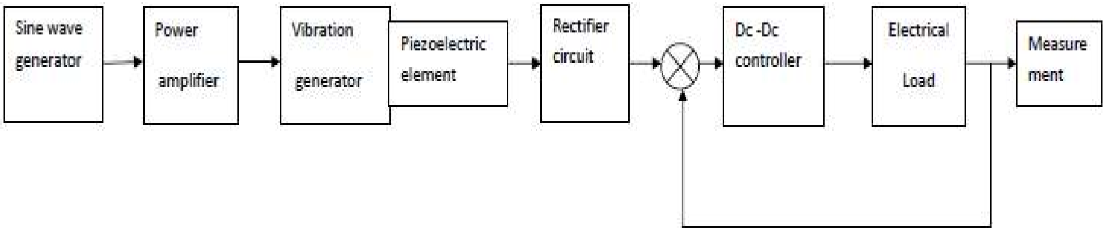


Fig7 Block Diagram of Lab experimental test setup.

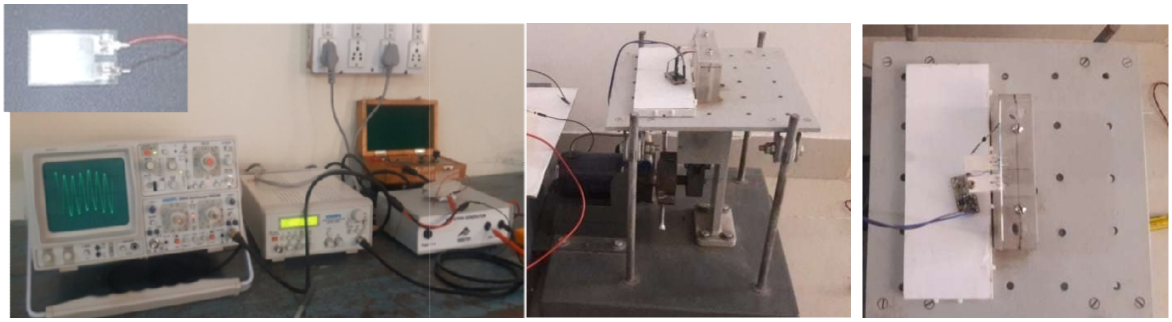
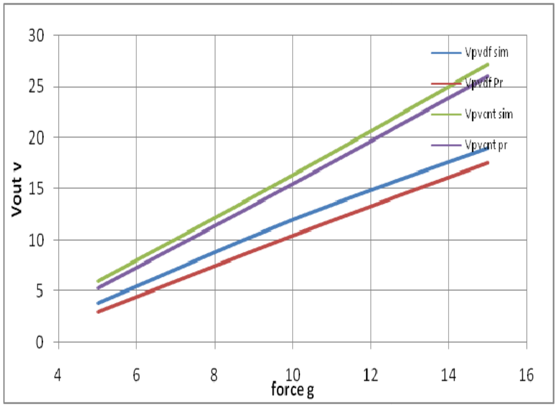
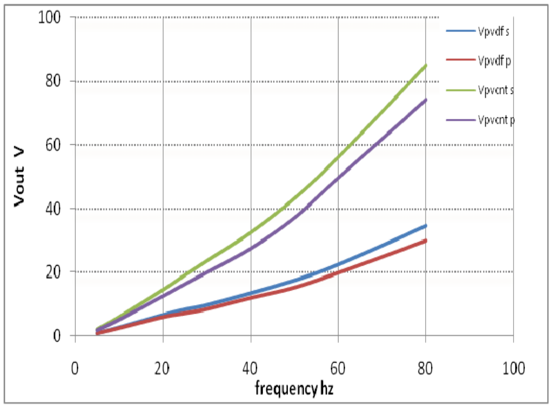


Fig:8 Experimental test setup(a)Lab setup (b) testing on mechanical vibration sources.

Comparison of PVDF-MWCNT with PVDF harvester module.



Fg: 9(a) PVDF and composite output Voltage at different input force



Fg: 9(b) PVDF and composite output voltage at different vibration frequencies

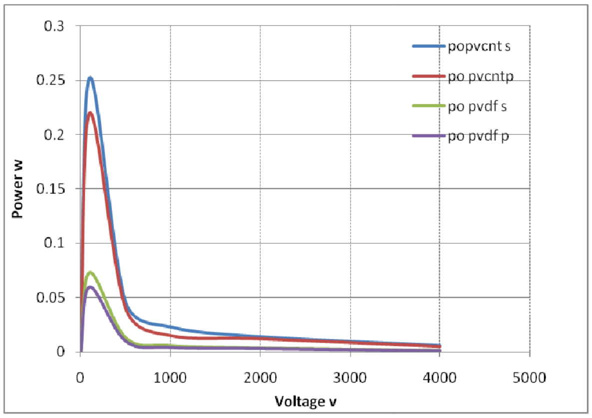


Fig:10(a) Power vs. R load plots of simulation and test Results of PVDF and composite

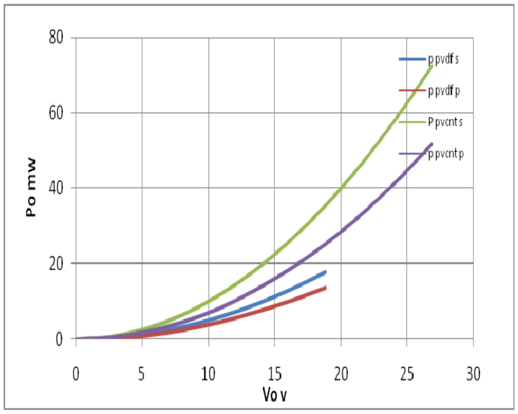


Fig:10(b) Power vs. R load plots of simulation and test results of PVDF and composite

Achievements with respect to objectives

A novel PVDF-MWCNT piezoelectric composite has been developed with optimized piezoelectric parameters like charge constant, modulus of elasticity, dielectric constant, electromechanical coupling coefficient. The newly developed composite generates voltage about 2 to 2.5 times higher than base PVDF material. A low loss self tuning circuit is proposed which has superior power flow in load circuit as compared to conventional convertor. A prototype Energy harvesting module has been prepared with developed novel composite and interfacing circuit. The new module increased the power flow in the load. circuit 3.5 times that of module consisting conventional bridge converter with PVDF element The novel mechatronic simulation model developed here reflects general behaviour and output of various piezoelectric materials with reasonable precision as compared to the electrical equivalent model.

Conclusion

PVDF-CNT Composite material developed in lab generates 2 to 2.5 times more voltage as compared to PVDF harvester. The proposed self tuned controller circuit increases power transfer 1.5 times as compared to conventional rectifier circuit. Energy harvesting module with novel composite and self tuned circuit shows overall gain of 3.5 in the extracted energy. The module is tested successfully with different vibration levels and input forces. A novel simulation model of piezoelectric generator has been developed and analytical expressions have been derived for mechatronic model. The simulation results are compared with hardware, previous work and simulation model. Experimental results validated mechatronic model developed in simulink. The results of this model are compared with electrical model used in past works which also indicate that developed simulation model predicts energy output more realistic. Mechatronic model developed in simulink incorporates most of the material properties and dimensions of harvester. Electromechanical coupling and mechanical damping effect of the harvester structure are crucial factors which have great impact on output of piezoelectric harvester. These two factors are also incorporated in new model developed in simulink. The proposed mechatronic model gives realistic results with an error of about 15% and can be used successfully to predict behaviour, response and output of different kind of piezoelectric harvester for the varied parameters. The mechatronic model results are compared with proposed hardware model and validated. The model is successfully implemented for analyzing energy harvested from different kinds of piezoelectric material harvesters with different parameters.

Paper Publications

1. Vrunda R Kotdawala, Dr. Vithal N Kamat “Optimization of Piezoelectric Properties of PVDF Polymer by Synthesis with MWCNT for Enhancing Piezo Electric Energy Extraction.” International Journal of Research and Analytical Reviews, Volume 6, Issue 2, 786-791, May 2019
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