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EXPERIMENTAL STUDY OF POWER HARVESTING FROM VIBRATION USING GIANT MAGNETOSTRICTIVE MATERIALS

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Keywords: Magnetorstriction, Vibration, Power Harvesting, Villari Effect, Terfenol-D, Magnetostrictive Electric Generator.

Abstract. *The interest in research and development of smart actuators, sensors and power generators that used Giant Magnetostrictive Materials (GMM) is growing. Both academia and industry are actively looking for bread utilization of GMM technology for different applications (active vibration and noise control, structural health monitoring, self-powered electronic equipments and systems, MEMS, robotics, etc.). In the paper we present results of experimental study of vibration-to-electric energy conversion using giant magnetostrictive materials. The magnetostrictive power harvesting device was built using Terfenol-D rod. The fundamental base for development of the device is a Villari effect. That is, by applying a mechanical stress to a magnetostrictive material, the magnetization along the direction of the applied stress of the material varies due to the magnetostrictive effect. The flux variation obtained in the material induces an emf in a coil surrounding the material. Test rig's measurement data have confirmed the expected function of the developed magnetostrictive power harvesting device. Electrical power of the device for different input parameters of external vibration field was examined. The experimental results are presented for Terfenol-D rod with 50 mm in length and 15 mm in diameter which have shown that efficiency of the developed magnetostrictive power harvesting device varies from 8% to 25%.*

1 INTRODUCTION

The history of magnetostriction began in the early 1840s when James Prescott Joule (1818-1889) identified the change in length of an iron sample as its magnetization changed. Magnetostriction is a transduction process where the electrical energy is converted to mechanical energy. It is called the *Joule effect* and is the most common magnetostrictive mechanism employed in magnetostrictive actuators. There exists also an inverse process in iron samples where mechanical energy is converted to electric energy. It is called the *Villari effect* and is used in the development of magnetostrictive sensors. Magnetostrictive materials exhibit a change in dimension when placed under a magnetic field. This is a result of reorientation of the magnetic domains, which produces internal strains in the material. The internal strain causes a change in length which can be controlled by the magnetic field. Giant magnetostriction was discovered in the basal planes of rare earth metals (Tb - terbium, Dy - dysprosium). The strains were about 0.6% (6000 ppm) at 150 K. The GMM are available in several alloys like Terfenol-D, Galfenol, Amorphous Tb-Fe based composites, Nanocrystalline Dy-Fe based composites. GMM are effective under a high bandwidth and at high operating temperature making them ideal for several applications. The Terfenol-D alloy was developed in the 1950's at the Naval Ordinance Lab, USA. It is an alloy of Terbium, Iron, and Dysprosium [1], (refer Table 1 for Terfenol-D properties [2]).

The physical configuration of the magnetostrictive generator is shown schematically in Fig. 1. Transduction process of MEG work cycle can be theoretically studied from the upper part of Fig. 2 showing magnetostriction (strain) as a function of magnetic field (H) and mechanical prestress. A change in the mechanical strain comprises of magnetostrictive and ordinary Hook's strains and is a result of the combined response of active material to magnetic field strength. The lower part of Fig. 2 shows magnetic induction B as a function of magnetic field (H) and mechanical prestress.

The Terfenol-D mechanical stress cycling output will be found in the coupled induction on the Fig. 2 (lower part) showing resulting delta-B and (B-H) changes inducing voltage and energy in the generator coil winding. By changing the mechanical stress level in the Terfenol-D results in coupled change in the magnetic induction (B). To counteract this change in B an electric current is induced in the coil creating a magnetic field (H). This field maintains B unchanged. If the coil would to have zero resistance this attempt would also be successful and

B would not change. When the coil load is between zero and infinite resistance, electrical energy will be taken out of the MEG. For a given stress cycle input driven by vibrations, e.g. a vibrating surface, a continuous output of electrical energy can be maintained for some closed loop applications. The external mechanical stress takes energy out of the system for transduction through the Terfenol-D into electric energy output. This braking force is created by induced magnetic field in addition to the changes in magnetic energy. In the case of loaded transformer secondary windings, the loaded circuit of MEG is reduced. This is because of induced opposing magnetic flux change and reduced the dB/dt rate.

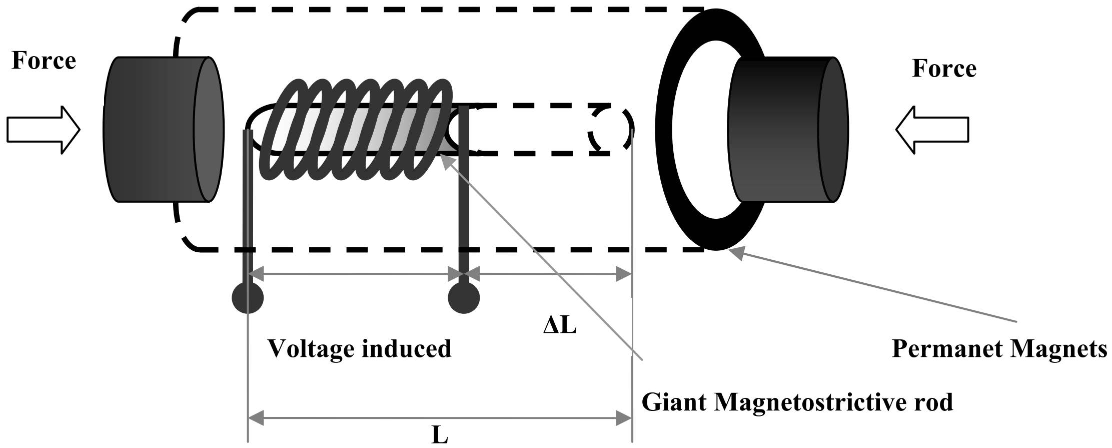

Figure 1. Schematic of principle of Villari effect

Properties	**Terfenol-D**
Energy Density, (kJm^{-3})	4.9-25
Effective Force in Terms of Mechanical Stress, (MPa)	5-70
Giant Magnetostriction, Strain, (μm)	max 6000
Bandwidth, (kHz)	<1
Hysteresis	~10%
Density, (kg/m^3)	9210-9250
Coupling factor, (-)	0.7-0.8
Young's Modulus, (GPa): at constant current at constant voltage	18-55 50-90
Compressive Strength, (MPa)	304-880
Tensile Strength, (MPa)	28
Relative Permeability, (-)	3-20
Curie Temperature, (C^0)	380
Material Resistivity, (μΩm)	0.6
Piezomagnetic Constant (nm/A)	5-15
Relative Magnetic Permeability, (-)	2-10
Sound Propagation speed (m/s)	1650-1950

Table 1 : **Properties of Terfenol-D** which is a composite from several published sources

When the coil is closed and loaded the induced (H) field will create additional opposing forces requiring higher force levels to compress the Terfenol-D to a required strain level than in case of open circuit coil design. The compression release lifting forces will be reduced and lowered as for the case of open circuit spring return. Hence more work is done when compressing the closed circuit coil and less work while decompressing as compared to the open circuit. Therefore the net energy consumed during the loaded coil work cycle corresponds to the dissipated mechanical input energy, which is consumed on the electrical side of the Terfenol-D energy transduction generator. The applied mechanical prestress is balanced by the induced coil current magnetic field to prevent magnetic dipole rotation, thereby changing B-field through the coil. Hence for a zero resistance coil the counter induced magnetic field will balance all mechanical forces. This makes the Terfenol-D infinitely stiff and no compression of the Terfenol-D will result from the applied mechanical prestress. Hence no work will be done. However, with a non-zero resistance coil, the electric and mechanical energies in the coil dissipate thereby reducing the stiffness of the Terfenol-D.

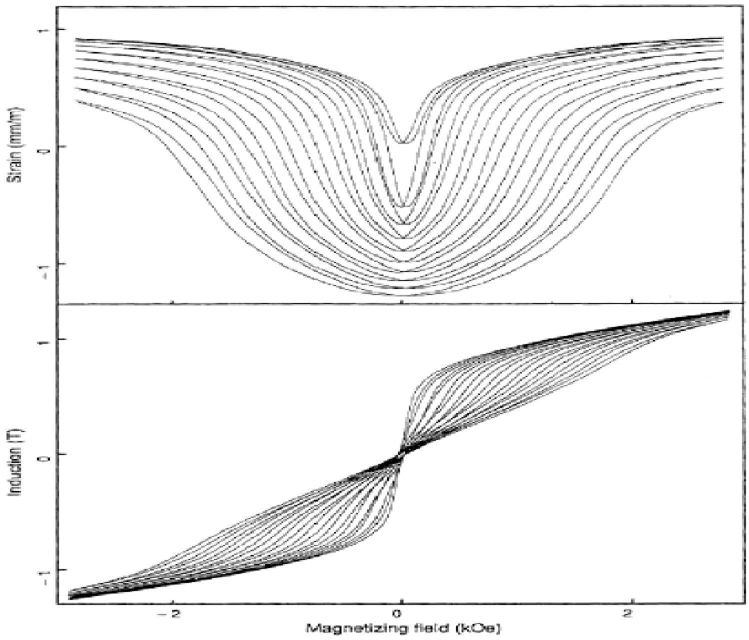

Figure 2. Typical Magnetostriction and magnetization curve of Magnetostictive material [2].

The increase in power harvesting research has brought many modern advances in wireless technology and low-power electronics such as MEMS. The use of piezoelectric materials to capitalize on the ambient vibrations surrounding a system is one method that has seen a dramatic rise in the use for power harvesting [3]. Due to its notable advantages of fast response time (micro-sec), it can be used over a wide range of frequency domains. GMM are capable of working stably under high Curie temperature, relatively high strain, low voltage operating conditions and show no ageing effects as compared to piezoelectric materials. Today magnetostrictive materials are used for a wide range of applications like high-power sonar transducers, high-speed hydraulic valves, inchworm for low frequency mechanical systems, and active control for vibrations on helicopter rotor motors [2].

The technology of conversion of mechanical vibrations to electric energy is not new. Several steps have been several steps taken in the past to design and optimize such systems. Researchers have used several approaches in combining the usage of active materials and low power electronics [4-6]. In the past, different smart materials have also been used in the electrical energy harvesting process. Piezoelectric materials have been used in micro scale applications. For instance, the power generated by the vibration of the piezoelectric is shown to be a maximum of 2 mW, and provide enough energy to charge a 40 mAh button cell battery in one hour [7]. The relationship between the electromechanical coupling coefficient, quality factor and power generation efficiency for the analysis of piezoelectric oscillators demonstrates the relative merit of changes to device structural stiffness, mechanical damping and mass in order to improve device efficiency [8]. Peak power efficiencies of 20% can be achieved from cantilever piezoceramic composite beams when coupled to a flyback converter [9], where the strain energy arising from mechanical vibrations is converted to useful electrical energy. Advanced Cerametrics Inc. demonstrated the feasibility of developing an energy harvesting system using piezoelectric fiber composite, which is able to recover waste mechanical energy (body motion, vibration, compression), convert it to useful electrical energy, and store it to charge other electronic devices. The simplest system consists of 4 multilayer composite transducers, connected in parallel, embedded in epoxy. Electronic circuitry is connected to the transducers, which extracts and stores the generated output voltage from the transducers. In the earliest tests an output voltage of 7.5 V with 0.9 mJ of energy was successfully stored in a capacitor (obtained from a 50 Hz vibration in about 3 minutes). At this stage, this energy is sufficient to power wireless sensors for a variety of applications including condition monitoring of areas in an aircraft that are inaccessible for replacement of batteries. Additional self-powered monitoring systems need to be substituted as a backup for aerospace, automotive, home appliance and biomedical applications [10]. The above technology is restricted to micro scale applications. Hence, it is needed to move on with experimental study with other GMM like Terfenol-D and Galefenol where new vistas can open up in both micro and macro applications. An attempt is made in this regard to explore the possibility and potential of Terfenol-D usage in MEG.

The main aim of the paper is to use the Villari effect phenomenon to design and build MEG and to study the vibration-to-electric energy conversion for different magnetic bias, mechanical prestress and frequency of external excitation. A special test rig was built where the MEG is excited by a cam with number of facets on one side and mechanical prestress on the other side, (refer to Fig.3).

The design concept of the MEG using Terfenol-D rod giving rise to varying flux hence inducing current in the coil wound around the rod and the problem of eddy current losses [4] are few hints from the past research work that have helped in designing the MEG at Chalmers University of Technology.

2 DISCRIPTION OF EXPERIMENTAL SETUP

The objectives of the experimental study are to evaluate the potential feasibility of the MEG built at Chalmers for power harvesting from vibration using magnetostrictive materials, and to have more basic knowledge for understanding the transduction processes in active materials.

The MEG was manufactured, assembled and installed. The Terfenol-D rod with length 50mm and 15mm in diameter is used as core element in MEG. The rod is subjected to mechanical prestress input, hence compressing it and forcing the magnetic dipoles to turn. The magnetization of Terfenol-D by permanent magnets can be varied with different number of magnets that are filled into the magazine. The Terfenol-D rod is fitted into a bobbin and a transformer coil is wound around it. The bobbin can be used as add on sub part to the assembly of the MEG. The change in magnetic field will result in induced electric current in the electrical coil.

The experimental setup comprises of the test rig, the MEG, Oscilloscope (HP, 4 channel 100 MHz), Amplifier, Frequency / speed controller of the motor, (Fig. 3). A high frequency test rig is used for vibration excitation of the Terfenol-D by a cam coupled to electric motor shaft. The facet on the cam profile is machined to give a sinus wave input to the MEG. The force sensor (4 strain gauges) is used to measure the mechanical force input to the MEG. The wiring arrangement is a Wheatstone bridge that is fixed to an adaptor and connected to the amplifier (Bridge amplifier). The data of the force and voltage as output can be obtained on the oscilloscope. Root mean square (RMS) multimeter is used to govern the mechanical prestress on the Terfenol-D. There is small DC signal that is generated in the strain gauge due to the sinus excitation by the cam to the plunger transmitting the vibration to the MEG. This signal is amplified in the amplifier and tuned for 1 volt = 1000 N scale after amplification, i.e. for every one volt measured on the oscilloscope when mechanical prestress is applied to the moving carriage 1000 N is the force that is obtained in the MEG [11]. The speed of the motor and hence the frequency of external excitation to the MEG is controlled by an electrical frequency converter. The output of the MEG is an AC voltage. The AC voltage can also be rectified and regulated to some cut of value of some choice by a voltage regulator.

The input parameters of the test rig that can be varied are frequency and amplitude of external vibration, and mechanical prestress, (refer to Table 2). Outputs are voltage, current and powers.

Parameters	Min	Max	Unit
Frequency of External Vibration, f	0	1200	Hz
Amplitude of External Vibration, a	0	0.003	m
Input External Excitation force, F	0	10000	N
Mechanical Prestress, F_0	0	4500	N

Table 2: Specifications of the test rig

There are two outputs signals that can be read on Lab View plots. The force sensor signal (red) is amplified for 1volt = 1000N on the amplifier (HBM ME10), (refer Fig.3). The second signal (blue) is the electric peak-to-peak voltage of MEG coil to rheostat where the resistance is set to $1\,\Omega$. This signal is then directed to a bridge (X-PC signal router) between the computer measurement card and scan signals rates. Frequency of the test rig is read with a probe that constantly converts the cam speed, (rpm) to Hz (see orange probe in Fig. 3). Strain gauge is used to measure the mechanical force applied to the MEG. This signal can also be read on the RMS multimeter.

Two type of Terfenol-D rod are used in the experiments. One rod has been laminated from four Terfenol-D pieces. The reason for the lamination is to minimize the eddy current losses in the Terfenol-D rod due to current circulating it the material. Another rod is a non laminated Terfenol-D rod from ETREMA products, Inc., USA, (refer Fig 4.)

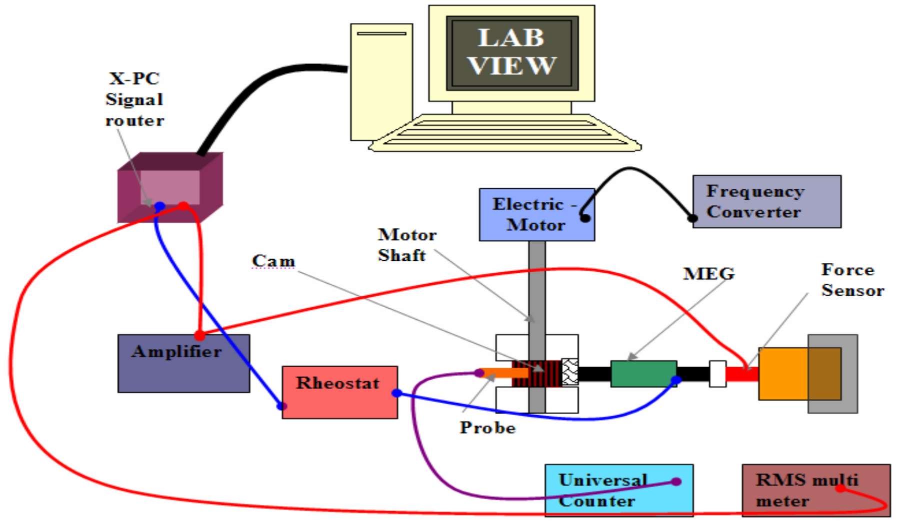

Figure 3. Experimental measurement set up for MEG

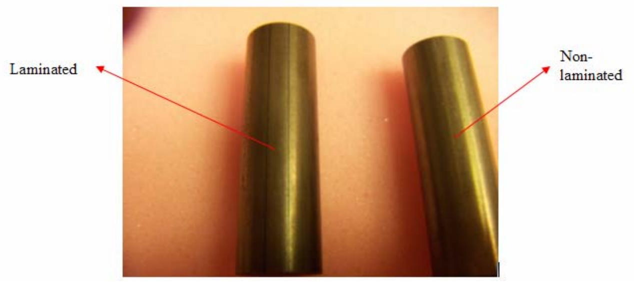

Figure 4. Terfenol-D rod samples

3 MEASUREMENTS

The experiments are carried out for Terfenol-D rod of length 50 mm and diameter 15 mm for laminated sample. The permanent magnets TBD alloy used to create magnetic bias for the Terfenol-D rod. The magnets are round shaped in 6 mm diameter and 2.5 mm height. Due to design restrictions the number of magnets that can be used are 320. The amplitude of excitation, *a,* was equal to 0.00135 m. It was measured by using a dial gauge on the cam facet.

Mechanical power input *(MPI)* and electric power output *(EPU)* were calculated by using the following formulae:

$$MPI = F * f * a, \tag{1}$$

$$EPU = \frac{((U_{pp})/2)^2}{R} \tag{2}$$

Here, F be the input external excitation force, in N, f be the frequency of excitation, in Hz, a be the amplitude of excitation, in m, U_{pp} be the peak-to-peak voltage, in V, R be the resistance, in Ω.

Efficiency of the MEG (Power Harvesting *PH*, %) is estimated by the following expression :

$$PH(\%) = \frac{EPU}{MPI} * 100 \tag{3}$$

4 RESULTS

The following graphs (Fig. 5 and Fig. 6) give a comparison between the *MPI Vs EPU* and power harvesting efficiency of MEG for different mechanical prestresses, input external excitation forces and frequencies. Here the coil resistance is equal to 1 Ω, (refer, Table 3 for the data).

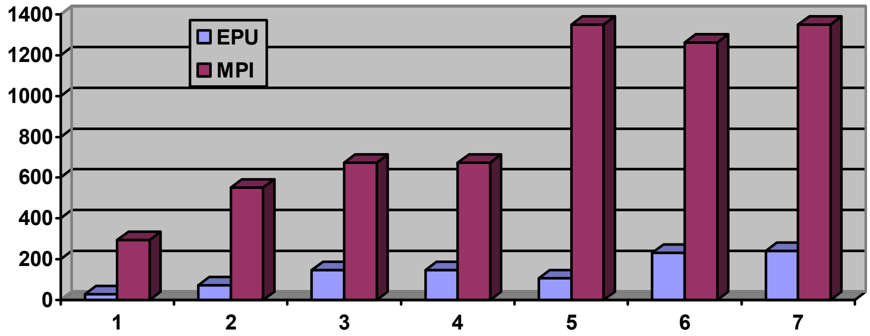

Figure 5. Bar chart comparison between *MPI Vs EPU*

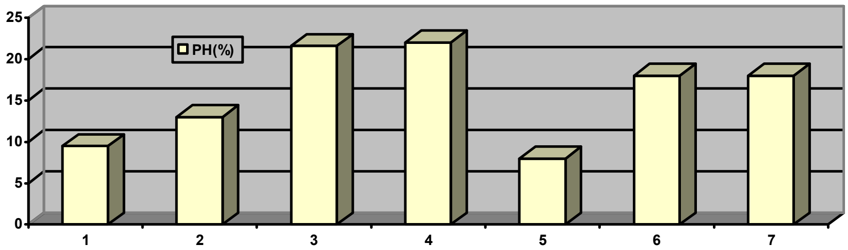

Figure 6. Bar chart for the PH (%) for each case listed in Table 3

Bar Number	1	2	3	4	5	6	7
Mechanical Prestress, N	1000	2000	2500	2700	2000	2500	3000
Input External Excitation Force, N	4365	8154	9995	9995	9995	9350	9995
Frequency, Hz	500	500	500	500	1000	1000	1000
MPI, W	294	550	647	674	1350	1262	1350
EPU, W	28	72.5	146	148	107	231	242
PH, %	9.5	13	22	22	8	18	18

Table 3: Data from measurements for circuit with resistance 1 Ω

In the Table 4 the data of experimentation with MEG for 0.5 Ω resistance coil are presented. The *MPI, EPU, PH* are calculated for different mechanical prestresses, input external excitation forces and frequencies.

Mechanical Prestress, N	1000	2000	2500	2000	2500	3000	3500	4000	4500
Input External Excitation Force, N	6528	7905	9155	9995	8476	9995	9995	9995	9995
Frequency, Hz	500	500	500	1000	1000	1000	1000	1000	1000
MPI, W	440	534	618	1350	1144	1350	1350	1350	1350
EPU, W	60	110	156	213	153	178	221	174	199
PH, %	14	21	25	16	14	13	16	13	15

Table 4: Data from measurements for circuit with resistance 0.5 Ω

Analysis of data of the Tables 3-4 shows that the maximum output power of the MEG is equal to 242 Watts.

From Fig. 7 (force Vs time curves for frequency 1000 Hz and for mechanical prestress 3000 N) it can be found that there is some additional force (thin curve) that builds up in addition to the mechanical prestress applied (thick curve). The sum of these forces is called input external excitation force. It's can be noted from curves in Fig.7 and Fig. 8 that the peaks of input external excitation force and the peaks of voltage with respect to time both rise in the same instants of time.

Analysis of experimental data has shown that Terfenol-D rod is sensitive to both mechanical prestress and frequency of external excitation, but more sensitive to frequency than mechanical prestress. For instance, increase in the mechanical prestress from 2000 N to 4500 N and keeping the frequency constant at 1000 Hz, there is about 30% fluctuation of *EPU* values, (see Table 4). This fluctuation appears as a saturation value when viewed on Fig 9 for 0.5 Ω curve. From the Table 3 and Table 4 it also follows that for mechanical prestress 2700 N and frequency 500 Hz the efficiency of the MEG was maximum for both 1 Ω and 0.5 Ω resistance, even though the *EPU* is lower than the highest *EPU,* (refer to Table 3, 6th row and 8th column). It may be right to assume that the MEG has not yet reached its highest potential limit for 1 Ω resistance circuit.

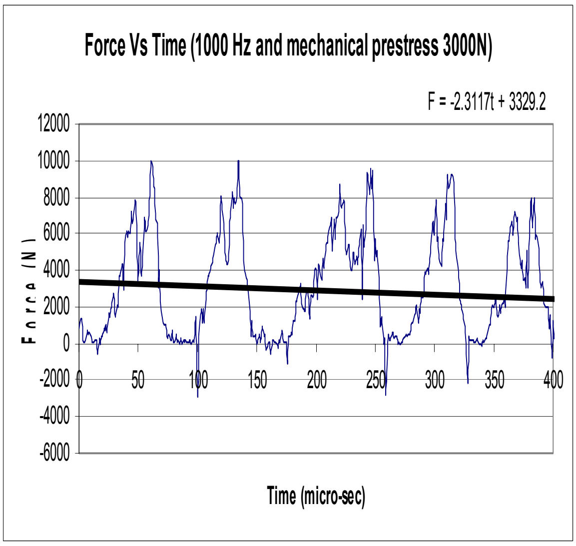

Figure 7. Force Vs Time for frequency 1000 Hz, and mechanical prestress 3000 N

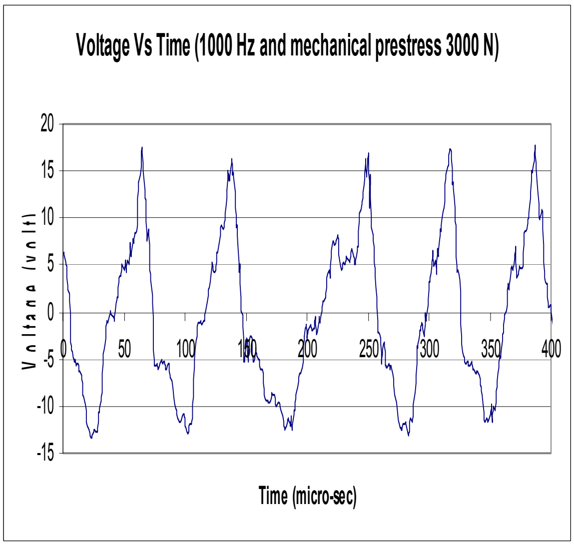

Figure 8. Voltage Vs Time for frequency 1000 Hz, and mechanical prestress 3000 N

The MEG voltage profile from Fig. 8 is sinus wave. To have MEG to charge a battery, there would be a need to have a rectifier to produce continuous power supply. The rectifier need to be designed considering for both rising voltages and also when the voltage saturates, and hence not effecting the power supply to the device, (actuator or sensor). It can be seen from Fig.10 that 0.5 Ω curve stabilizes for 10 volts output where as 1 Ω circuit voltage still seems to rise. It is also observed from Fig. 9 and Fig. 10 that voltage outputs are higher for 1Ω circuit compare to 0.5 Ω circuit.

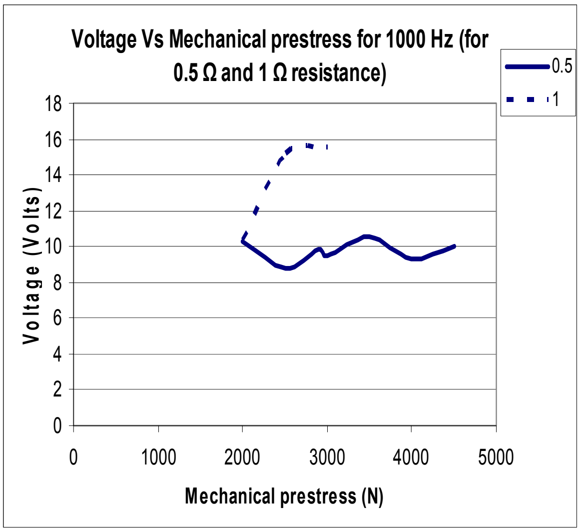

Figure 9. Voltage Vs mechanical prestress for 1000 Hz, 0.5 Ω and 1 Ω resistance

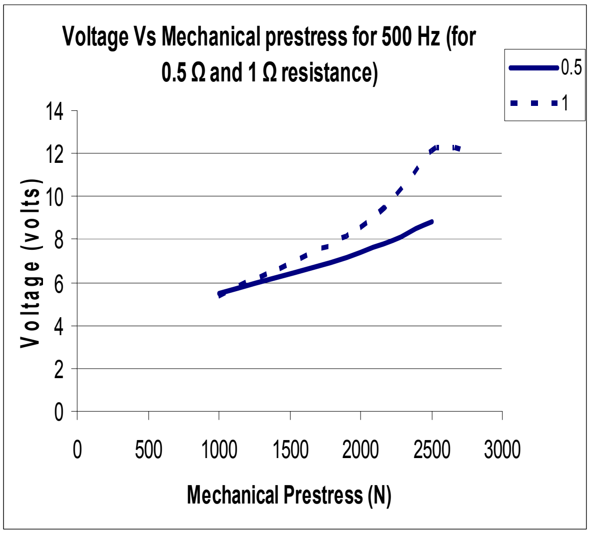

Figure 10. Voltage Vs mechanical prestress for 500 Hz, 0.5 Ω and 1 Ω resistance

5 CONCLUSION

The MEG was built based on the utilization of the Villary effect. Several experiments demonstrated its functionality to produce electric power for varying mechanical prestress and frequency of external excitations. The maximum electric power obtained was 242 W. For different mechanical prestresses and frequencies of external excitations considered the efficiency of the created MEG varies from 8% to 25%, (see data in Table 3 and Table 4). It was found that the transduction processes in Terfenol-D are more sensitive to the frequency of external excitations than to the mechanical prestress. The obtained results of experimental study of vibration-to-electric energy conversion using Terfenol-D demonstrate the potential of using giant magnetostrictive materials for harvesting power from vibration. These results can also be used for verification and validation of the mathematical models of magnetostrictive electric generators for predicting their performance and optimization of the generator design.

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REFERENCES

[1] L. E. Faidley, B. J. Lund, A. B. Flatau , F. T. Calkins, "Terfenol-D elasto-magnetic properties under varied operating conditions using hysteresis loop analysis, SPIE Symposium on Smart Structures 3/98 Paper No. 3329 92.

[2] G. Engdahl (2000), *Hand of Gaint Magnetostictive Materials* Acadamic Press, San Diego, USA.

[3] H. A Sodano, Inman D.J. and G. Park, A review of power harvesting from vibration using piezoelectric materials, *The Shock and Vibration Digest,* **Vol. 36,** No.3, May 2004, 197-205

[4] A. Lundgen, H. Tiberg, L. Kvarnsjö, A. Bergqvist, "A Magnetostictive Electric Generator" IEE Transactions on mangetics, Vol. 29, No.6, November 1993.

[5] S. Meninger, J. O. Mur-Miranda, R. Amritharajah, A. Chandrakasan and J. Lang, "Vibration- to- Electric Energy Conversion", Massachusetts Institute of technology, Cambridge, MA 02139.

[6] J. M. H. Lee, S. C.L Yuen, M.H.M. Luk, G. M.H.Chan, K. F. Lei, W. J. Li, P. H.W Leong, and Y. Yam, "Vibration-to-Electric Power Conversion Using High-Aspect-Ratio MEMS Resonators", *Published in the Proceedings of Power MEMS 2003, Chiba, Japan, December 2003 ,(ITF/185/01).*

[7] H. Sodano, E. A. Magliula, G. Park, D. J. Inman, "Electric Power Generation using Piezoelectric Devices", Center for Intelligent Material Systems and Structures, Virginia Polytechnic Institute and State University Blacksburg, VA 24061-0261, USA.

[8] C. D. Richards, M. J. Anderson, D. F. Bahr1 and R. F. Richards, "Efficiency of energy conversion for devices containing a piezoelectric component" Institute of Physic Publishing, Journal of Micromechanics and micro engineering, Published 17 March 2004, Online at stacks.iop.org/JMM/14/717 (DOI: 10.1088/0960-1317/14/5/009).

[9] A. Kasyap, J. Lim, D. Johnson, S. Horowitz, T. Nishida, K. Ngo, M. Sheplak, and L. Cattafesta, "Energy Reclamation From A Vibrating Piezoceramic Composite Beam", University of Florida Gainesville, FL USA 32611-6250, Ninth International Congress On Sound And Vibration, ICSV9.

[10] http://acer.inforest.com/pdf/adcera/aci_fiber_technology.pdf (May 01' 2005), Advance Cerametrics Incorporated, Advance Material Technology company, Piezoelectric Ceramic Fibers**.**

[11] K. Hoffmann (1989), *An Introduction to measurements using Strain guages,* Hottinger Baldwin Messtechnik GmbH, Darmstadt.