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Performances of rainfall energy harvester

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***Abstract* –In this paper the performances of rainfall energy harvesting by means of piezoelectric transducers is presented. Diverse studies agree on the level of suitable generated voltage on the electrodes of a piezoelectric transducer subjected to rainfall, but a complete characterization on the supplied power is still missing. This work, in order to limit optimistic forecasts, takes into account the behavior of the transducers subjected to real and also artificial rainfall, condition that has shown promising behavior in laboratory. In order to increase the energy harvesting and also define its limits different loads have been taken into account. Only commercial transducers have been considered: a lead zirconate titanate and polyvinylidene difluoride transducer.**

I. INTRODUCTION

In recent years an increasing attention to the possibility of generating energy without the use of conventional electric battery, led the study on the employment of smart materials. The use of renewable energies such as solar and wind power seems to be the best way to ensure the requirements for the achievement of high levels of power and a reduced environmental impact, even leading to innovative research topics concerning power quality measurements under electromagnetic emissions [1-5]. On the other hand a study on an alternative energy harvest can be taken: the piezoelectric materials seem to be the most suitable solution for the low power supply. The basic idea is to convert the mechanical energy of vibration or pressure into electrical energy. Different scenarios have been considered: in [6] a study on the harvested energy from vibrating shoe-mounted piezoelectric cantilevers is presented, it is a first integration of the harvesting energy in the human body; in [8] the energy harvesting from the vibrations of bridges is faced and so a weak point can be transformed into a resource; in [8] the harvesting of energy induced from the deformation of pavements due to moving vehicles is analyzed to recover energy in busy roads; in [9] the harvesting from automotive tires is discussed when such systems are already used to evaluate the tire status; in [10] a harvesting from seismic mass is presented and also an optimization is discussed; in [11] an innovative piezoelectric grass energy harvester is proposed; in [12] the energy harvesting from low frequencies travelling sound is presented, in [13] the wind energy harvesting is studied. Also the rainfall energy harvest has been faced [14-23]. The idea is to convert, by means of piezoelectric plates, the kinetic energy possessed by the drops of rainwater into electrical energy. A pioneering comparison of different piezoelectric materials, in order to investigate the possibility of energy generation water droplets energy sources for low power electronic devices, has been studied in [16]. These studies agree that the single drop of water hitting the piezoelectric plates generates voltages less than a dozen of volts (peak to peak, and without load), but no evaluation on power has been proposed. The drops of rain strike the piezoelectric material in a cantilever configuration, which may be subject to study to improve the energy produced [24-26]. Although the voltage peak to peak, produced by droplets, seems high enough to interact with electronic devices or rectifiers a more accurate characterization is required, in order to dispel excessive optimistic predictions.

There are still doubts about the ability to feed power devices, and in order to explore this concept it is useful to use the concept of energy flow [27,28] clarifies the dissipation of energy during the harvesting process, in order to separate the electromechanical coupling coefficient of the system, natural frequencies, damping ratio and electric load. Also a good survey on the optimal AC–DC power generation for a rectified piezoelectric device and] the problem of the storage energy is presented in [29-31]. It is clear that the average harvested power particularly depends on the input vibration, larger surfaces allows greater impact areas, and a potentially higher collected power, but the cantilever configuration has its optimal geometrical structure [32-40]. A more definite analysis will concern the behavior of the device in the presence of strong stresses in terms of the electromagnetic field [41-42], by modeling the device as a receiving antenna [43-46]].

II. PIEZOELECTRIC MATERIALS AND MODEL

Piezoelectricity is a property present in many materials: the generation of an electric charge in certain non-conducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration) is known as direct piezoelectric effect, whereas the generation of vibrations in such materials when they are subjected to an electric field is the inverse effect. The ability of piezoelectric

materials to convert electrical energy into mechanical and vice versa depends on their crystalline structure. The necessary condition occurs because the piezoelectric effect is the absence of a center of symmetry in the crystal, which is responsible for charge separation between positive and negative ions and the formation of the Weiss domains. It is beyond the scope of this study provide an exhaustive description of the phenomenon, interesting discussion can be found in [28]. In this study the energy harvester consists of a piezoelectric film on an epoxy cantilever sandwiched between electrodes that are used to collect the generated power. When the piezoelectric material is subjected to mechanical vibrations, stress is induced within the material, thus giving rise to an electromotive force that generates an electrical impulse. The application of force brings the internal lattice structure of the piezoelectric element to deform, causing the separation of the centers of molecular gravity, and therefore to the generation of small dipoles, which global effect is taken into account by considering an ideal transformer which correlates stress to voltage. A sheet of piezoelectric material has some limitations in the mechanical-electrical transduction for low-frequency signals, since it fails to generate pulses at high pressure when the sheet is very large.
In following work two different types of piezoelectric materials have been taken into consideration: piezoelectric ceramic Lead Zirconate Titanate (PZT) and polyvinylidene difluoride (PVDF), [46,47]. This choice was made to try to provide a comprehensive overview of the possibility to extract energy from precipitation by employing commercial harvester. Indeed, the presence of lead in PZT transducer places him among the materials shall not be used to avoid contaminating the environment. The choice to use commercial harvester limits shape and configurations, but also the thickness of the layer of piezoelectric film.

Different transducers configuration can be used. In Fig.1 the one and two bound edge cantilevers are shown.

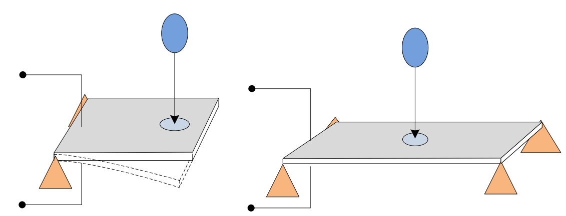

Fig. 1- Piezoelectric cantilevers, one edge bound on the left, two edges on the right.

Larger collection surfaces can be used as the ones adopted in [20] and [22].

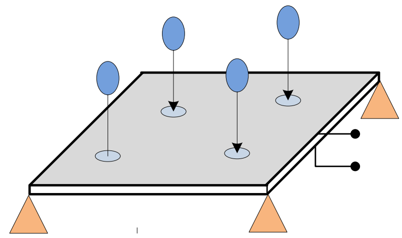

Fig. 2- Piezoelectric collecting surface adopted in [20].

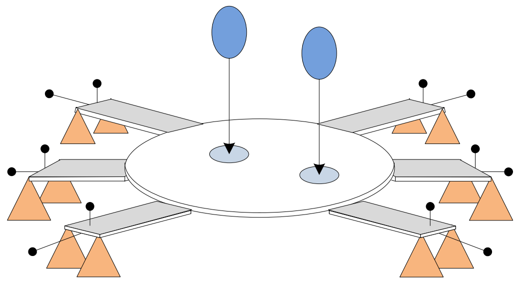

Fig. 3- Collecting diaphragm and piezoelectric cantilevers adopted in [22].

In [22] different thickness layers have been simulated by employing finite element method. In [20] a finite differences approach is performed.

The piezoelectric harvester can be considered as a charge generator or a voltage generator. When the piezoelectric film is subjected to a pressure due to the droplet, inside charges are generated which give rise to an electric field. The electrodes that are located close to the surface, are affected by this field and accumulate on their faces a quantity of charge proportional to pressure. At this point the role of the transducer may be interpreted differently depending on the type of load that is connected at its ends: if the load has an input impedance very low, the charges that accumulate on the electrodes are poured entirely on it, similarly to a charge generator; if the piezoelectric material is connected to a high-impedance load the charges remain confined on the faces of the sensor thus keeping the electric field unchanged, as in a voltage generator. A suitable equivalent electrical model can be that of a voltage source in series with a capacitor or the equivalent Norton's one. Also a resistance R_e that connects the two ends of the active component can be used to refine the model, so introducing the electrical loss. In order to define the behavior of the electromechanical transducer also the mechanical part has to be modeled, Fig.4.

In the mechanical part the inductor L_m represents the equivalent mass and the inertia of the piezoelectric generator, R_m represents the mechanical losses, C_m represents the mechanical stiffness, stress generator is caused by mechanical vibration, n is the transformation ratio of the transformer equivalent, element that relates the physical quantities with those electrical [33,48]. C_e

represents the capacitance of the piezoelectric element and V is the voltage across the piezoelectric transducer. Electric and mechanical parameters depend on the shape of the piezoelectric transducer.

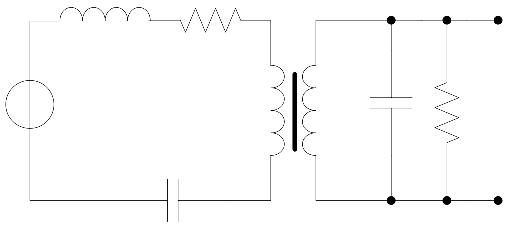

Fig. 4 Equivalent electro-mechanical scheme.

Many models in the literature have a harvester with an edge attached to a vibrating surface, and another bound to a mass; the relative movement of the two extremes realizes the bending [28, 34]. A model of a harvester, not attached to a vibrating surface, with an extreme urged by impulsive force is presented in [19].

Different studies in the literature show encouraging results with regard to the generation of electricity from water droplets [14-16]. The piezoelectric transducers can reach tens of volts, but this result does not yet allow to attribute to them the character of power generators. The water drops continuity in the same place is very variable: there may be intervals of seconds (small rainfall) or fractions of seconds (downpour). Table 1 of [23] reports a voltage varying from 1.6 to 98 V, depending to the radius of the droplets (0.5 to 2.5 mm), and also a power varying from few μW to some mW. Such harvested power can be used to feel transmission systems devoted to environment survey.

Different performances due to variable drops dimensions (mass) and impact point make hard to model the phenomenon. The voltage has a peak waveform, not a continuous voltage, so an equivalent average voltage has to be defined. For a power system the equivalent average current can be obtained by using a bridge rectifier and a smoothing capacity; for the theoretical model initially this approach has been not considered. To evaluate the power output of a piezoelectric transducer is necessary to define a range of possible stresses. The single drop of water can have a diameter that varies between 0.2 to 6 mm. Considering a cruise speed on impact of approximately 2 m/s for the small drop and 9 m/s for the largest, it is possible to estimate the energy input: E_{min} = 3.1μJ , E_{max} =0.063 J. Also considering the interval of two seconds to have a successive drop, the power is: P_{min} = 1.5μW , P_{max} =0. 031W., which can confirm the data in the table 1 of [23].

The removable power, however, is affected by several factors. The drop, while centering fully the piezoelectric film, is not able to transfer maximum energy as it is subject to the phenomenon of splashing: the collision is not complete since the impact surface are separated some small drops. It must therefore associate an efficiency of a collision. In the same way we should introduce a performance of the electrical-mechanical system. The drop stresses the piezoelectric according to the 31 mode and not all the energy is converted into charges on the plates of the transducer. Finally an electrical performance coefficient is to be introduced to take into account the losses of the rectifying bridge. The output power is given by:

$P_{out} = \eta_{collision} \cdot \eta_{piezo} \cdot \eta_{rect} \cdot P_{max}$.

The output power is certainly reduced, then the objective is to maximize it.

III. EXPERIMENTAL STUDY

The transducers on which the experiments were conducted are Mide Volture V22B and V22BL [47] and the MEAS LDT1-028K [48]. Volture the sensors were mounted in a suitable support, caged to extremes, due to their fragility. The sensor Meas was mounted as a cantilever in a suitable support.

Fig. 5 and 6 show the piezoelectric transducers. The PVDF Meas is customable, the PZT Volture has a rigid structure and no modification can be introduced.

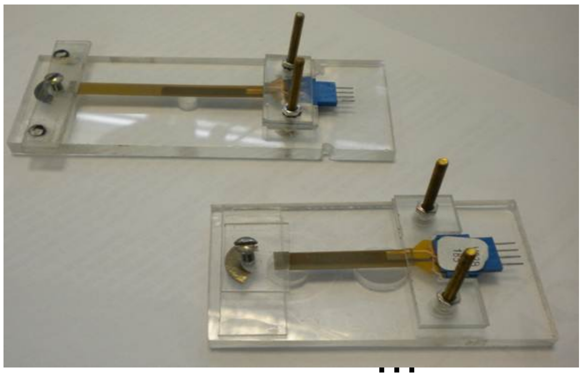

Fig. 5 Lead zirconate titanate (PZT) transducers: V22BL in the top and V22B in the bottom of the picture.

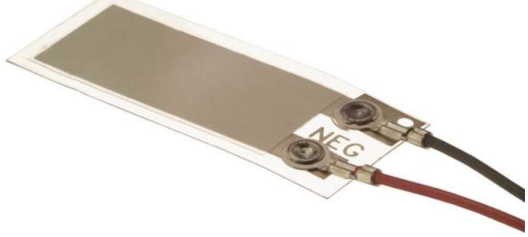

Fig. 6 Meas LDT1-028k polyvinylidene difluoride (PVDF) transducer.

The piezoelectric transducers were fixed on suitable support and were exposed to real and artificial rain. In this condition were measured the voltage values generated by the impact of the droplets. Roughly some typical generated waveforms are definable: transducers bound to the both ends have generated waveforms more regular, in which a first pulse largest is followed by a second smaller and of opposite sign, Fig.7.

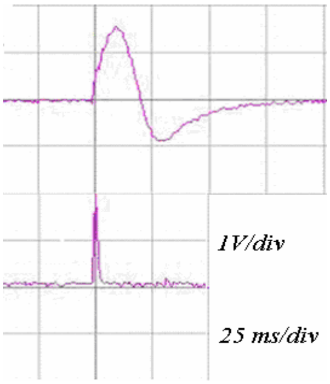

Fig. 7 Two signals acquired for the PZT transducer: the first presents the typical behavior, a large positive pulse followed by a second smaller; the second acquired signal presents only positive pulse. The waveform of the signals is often conditioned by the presence of the water film on the transducers.

Sometimes the second pulse has been followed by a third and sometimes was not present. In some cases we have obtained single peaks, this physical behavior has required a bit more attention since the physical stress did not change, but it happened to the tension. It was found that the negative or positive peaks of tension occurred in correspondence with a state of piezoelectric plate already burdened with a water film, as a result of impact the compression status ranged, generating a negative or positive peak of voltage.

The PVDF piezoelectric sensor has been used in cantilever configuration. An output voltage is represented in Fig. 8. The output voltage has an oscillating behavior, due to the presence of an underdamped system. The energy of the drop of water is absorbed and then released to the electrical system in a longer interval than that used by the Volture transducers. In both cases the performances were conditioned by the presence of an irregular water film on the transducers with a mass increase and with that a damping increase.

The voltage levels were maintained with maximum peaks of 4 volts during the different tests. Such voltage might seem high, but refers to a peak to peak value, and it has been found for the artificial rain mainly. Another feature to be investigated is the frequency of the voltage: cantilever transducers show an underdamped behaviour, transducers bound in both ends an overdumped one.

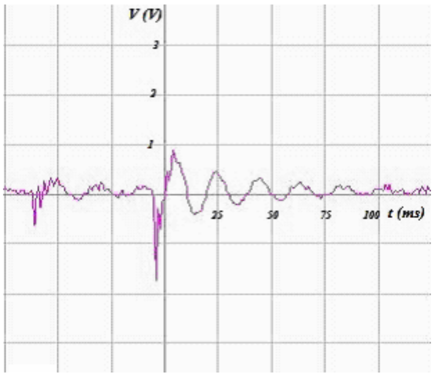

Fig. 8 Waveform of the voltage given by a PVDF transducer in cantilever configuration. Oscillations are due to the particolar structure.

To characterize the behavior of the transducers were carried out some measures by placing different resistive load connected to the electrodes. Ten measurements for each load were considered useful. The output parameter of the experiments is given by the power exchanged during the impact.

In order to compare the behaviour of the different test the average power on the resistor has taken into account and not the voltage time profile. In order to compare the different behavior of the PZT and PVDF transducers, it was decided to refer both to the same conditions, thus using mostly artificial rain, which is more easily reproducible with the same characteristics. In Fig. 9 the power extracted from the single drop of water, in the case of PZT transducers, for to the loads of 10, 33, 47, 68, 82, 100, 180,270, 470 kΩ is represented. The two transducers have values of comparable powers, this is due to the fact that both have equal amplitude of piezoelectric material, while it varies the length of the material which constitutes the shell.

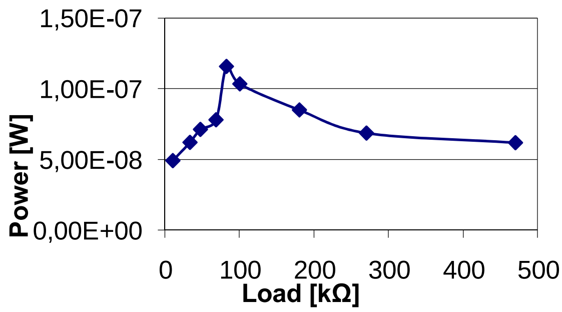

Fig. 9 Power extracted from single drop of water using the PZT transducers.

In Fig. 10 the power extracted from the single drop of water, in the case of PVDF transducers, for to the loads 10, 22, 47, 100, 180, 470 kΩ is represented.

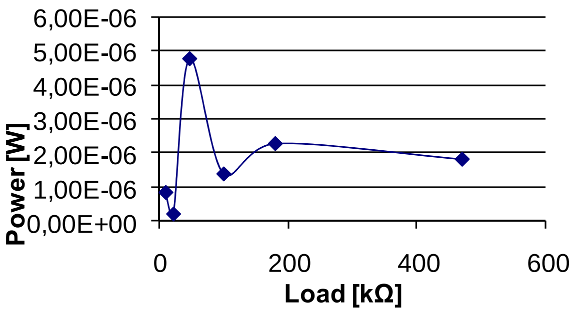

Fig. 10 Power extracted from single drop of water using the PVDF transducer.

IV. DISCUSSION

The harvested power can be used to feed low-power consuming devices such transmitting ones. A way to improve the harvested power is to change the geometry of the cantilever. As suggested in [39] to maximize the energy conversion is not important to cover the largest area, but to subject the piezoelectric material close to its strength limits. The conventional rectangular harvester cantilever has a bending moment which decreases linearly from the fixed edge to the free one. A trapezoidal shape will allow to obtain a much regular moment, in such a way the PVDF harvester can be easily modified. In figure 20 the original and the custom shape of the meas PVDF harvester, are schetked.

The custom shape has an area reduced of 20% respect the original one.. In such a way it is possible to deduce

that the power can be maximized by using a smart geometry. In order to improve harvested power the cantilever surface can be pressed against a suitably shaped profile, given by a cylindrical surface, as shown [40], figure 12.

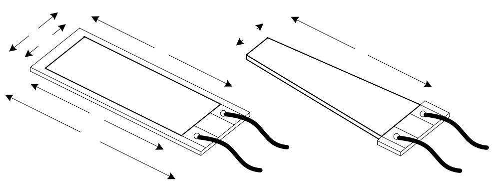

Fig. 11. Original PVDF cantilever: Le = 30 mm, Lb = 34 mm, Ltot = 4.2 mm, W =16 mm, We = 12mm. Custom shape: Wc = 8mm.

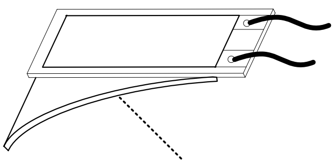

Fig. 12. PVDF cantilever and pressing surface.

V. CONCLUSIONS

This paper reports a study on the piezoelectric energy harvesting of rainfall and its limits. Two types of commercial piezoelectric transducers were considered: Lead Zirconate Titanate (PZT) and polyvinylidene difluoride (PVDF). A comparison of power output available at terminals of the transducer has been performed by considering two different PZT transducers, a single and a double PVDF transducers; this comparison has shown that the single transducer PVDF generates a greater amount of power. Customization have been suggested to improve the harvested power.

REFERENCES

[1] Cipriani G., Miceli R., Spataro C., “Uncertainty Evaluation in the Measurements for the Electric Power Quality Analysis”, Proceedings of the International Conference on Renewable Energy Research and Applications (ICRERA), 20-23 October 2013, Madrid, Spain, pp.1-6

[2] Cipriani G., Miceli R., Spataro C. , Tinè, G. , "Electric Power Quality Evaluation in the Presence of Electromagnetic Emissions", Proceedings of the International Conference on Renewable Energy Research and Applications (ICRERA), 20-23 October 2013, Madrid, Spain, pp.1-6.

[3] P. Romano, F. Viola, , R. Miceli, C. Spataro, B. D’Agostino, A. Imburgia, D. La Cascia, M. Pinto: “Partial Discharges on IGBT Modules: are sinusoidal waveforms sufficient to evaluate behavior?”, 2014 IEEE Conference on Electrical Insulation and Dielectric Phenomena, CEIPD 2014, Des Moines, Iowa, USA, OCTOBER 19-22, 2014

[4] Boscaino, V., Miceli, R., Capponi, G., Casadei, D., “Fuel cell modelling and test: Experimental validation of model accuracy”, International Conference on Power Engineering, Energy and Electrical Drives, art. no. 6635890, pp. 1795-1800.

[5] Boscaino, V., Miceli, R., Capponi, G., Ricco Galluzzo, G., Rizzo, R., “Fuel cell analytical modeling: Solving the trade-off between accuracy and complexity”, Przeglad Elektrotechniczny, 89 (11), pp. 220-224, 2013

[6] L Moro and D Benasciutti, “Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers”, 2010 *Smart Mater. Struct.* 19 115011 doi:10.1088/0964-1726/19/11/115011

[7] Michaël Peigney and Dominique Siegert, “Piezoelectric energy harvesting from traffic-induced bridge vibrations”, 2013 *Smart Mater. Struct.* 22 095019 doi:10.1088/0964-1726/22/9/095019

[8] H J Xiang, J J Wang, Z F Shi and Z W Zhang, “Theoretical analysis of piezoelectric energy harvesting from traffic induced deformation of pavements”, 2013 *Smart Mater. Struct.* 22 095024 doi:10.1088/0964-1726/22/9/095024

[9] D A van den Ende, H J van de Wiel, W A Groen and S van der Zwaag, “Direct strain energy harvesting in automobile tires using piezoelectric PZT–polymer composites” 2012 *Smart Mater. Struct.* 21 015011 doi:10.1088/0964-1726/21/1/015011

[10] E Jacquelin, S Adhikari and M I Friswell, “A piezoelectric device for impact energy harvesting”, 2011 *Smart Mater. Struct.* 20 105008 doi:10.1088/0964-1726/20/10/105008

[11] J D Hobeck and D J Inman, “Artificial piezoelectric grass for energy harvesting from turbulence-induced vibration”, 2012 *Smart Mater. Struct.* 21 105024 doi:10.1088/0964-1726/21/10/105024

[12] Bin Li, Jeong Ho You and Yong-Joe Kim, “Low frequency acoustic energy harvesting using PZT piezoelectric plates in a straight tube resonator”, 2013 *Smart Mater. Struct.* 22 055013 doi:10.1088/0964-1726/22/5/055013

[13] Nan Wu, Quan Wang and Xiangdong Xie, “Wind energy harvesting with a piezoelectric harvester”, 2013 *Smart Mater. Struct.* 22 095023 doi:10.1088/0964-1726/22/9/095023

[14] Thomas Jager, Romain Guigon, Jean-Jacques Chaillout and Ghislain Despesse, “Harvesting raindrop energy: theory," IOPscience, 2008.

[15] Thomas Jager, Romain Guigon, Jean-Jacques Chaillout and Ghislain Despesse, “Harvesting raindrop energy: experimental study," IOPscience, 2008.

[16] D Vatansever, R L Hadimani, T Shah and E Siores, “An investigation of energy harvesting from renewable sources with PVDF and PZT”, IOP Publishing, 2011.

[17] F. Viola, P. Romano, R. Miceli, G. Acciari, “Harvesting rainfall energy by means of piezoelectric transducer”, International Conference on CLEAN ELECTRICAL POWER Renewable Energy Resources Impact 2013, June 11-13 2013, Alghero, Italy

[18] F. Viola, P. Romano, R. Miceli, G. Acciari, “On the harvest of rainfall energy by means of piezoelectric transducer”, 2nd International Conference on Renewable Energy Research and Applications, ICRERA. Madrid, Spain, 20-23 October 2013.

[19] F. Viola, P. Romano, R. Miceli, G. Acciari, Ciro Spataro,“Piezoelectric model of rainfall energy harvester” 2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monaco, 25-27 March 2014.

[20] K. C. R. Perera B.G.Sampath, V.P.C. Dassanayake, B. M. Hapuwatte, Harvesting of Kinetic Energy of the Raindrops, International Journal of Mathematical, Computational, Physical and Quantum Engineering Vol.8 No.2, 2014

[21] M. Al Ahmad and G. E. Jabbour, Electronically droplet energy harvesting using piezoelectric cantilevers, Electronics Letters, vol. 48, pp. 647-649,2012

[22] Wong Chin-Hong, Dahari, Z. ; Abd Manaf, A. ; Sidek, O. ; Miskam, M.A. ; Mohamed, J.J., Simulation of piezoelectric raindrop energy harvester, TENCON Spring Conference, 2013 IEEE, 465 – 469, 2013.

[23] Aashay Tinaikar, Harvesting energy from rainfall, International Journal of Renewable and Sustainable Energy, 2013; 2(3): 130-132

[24] Swee-Leong Kok, Neil M White and Nick R Harris, “Fabrication and characterization of free-standing thick-film piezoelectric cantilevers for energy harvesting” , 2009 *Meas. Sci. Technol.* 20 124010 doi:10.1088/0957-0233/20/12/124010

[25] Quan Wang and Nan Wu, “ Optimal design of a piezoelectric coupled beam for power harvesting”, 2012 *Smart Mater. Struct.* 21 085013 doi:10.1088/0964-1726/21/8/085013

[26] Yabin Liao and Henry A Sodano, “Optimal placement of piezoelectric material on a cantilever beam for maximum piezoelectric damping and power harvesting efficiency”, 2012 *Smart Mater. Struct.* 21 105014 doi:10.1088/0964-1726/21/10/105014

[27] Junrui Liang and Wei-Hsin Liao, „Energy flow in piezoelectric energy harvesting systems”, 2011 *Smart Mater. Struct.* 20 015005 doi:10.1088/0964-1726/20/1/015005

[28] Alper Erturk and Daniel J. Inman, “Piezoelectric energy harvesting”, John Wiley & Sons, USA, 2011.

[29] Y C Shu and I C Lien, “Analysis of power output for piezoelectric energy harvesting systems”, 2006 *Smart Mater. Struct.* 15 1499 doi:10.1088/0964-1726/15/6/001

[30] A D Schlichting, E Fink and E Garcia, “A low-loss hybrid rectification technique for piezoelectric energy harvesting”, 2013 *Smart Mater. Struct.* 22 095028 doi:10.1088/0964-1726/22/9/095028

[31] M J Guan and W H Liao, “On the efficiencies of piezoelectric energy harvesting circuits towards storage device voltages”, 2007 *Smart Mater. Struct.* 16 498 doi:10.1088/0964-1726/16/2/031

[32] Roundy S, Wright P K and Pister K S J “Micro-electrostatic vibration-to-electricity converters” ASME IMECE, New Orleans, LA, Nov. 2002

[33] E. Brusa, S.Zelenika,, L. Moro, D. Benasciutti, “Analytical characterization and experimental validation of performances of piezoelectric vibration energy scavengers”, Smart Sensors, Actuators and MEMS IV, 2009

[34] S Roundy, P K Wright, “A piezoelectric vibration based generator for wireless electronics”, INSTITUTE OF PHYSICS PUBLISHING Smart Mater. Struct. 13 (2004) 1131–1142

[35] R. Littrell, K. Grosh, “Modeling and Characterization of Cantilever-Based MEMS Piezoelectric Sensors and Actuators”, Journal Of Microelectromechanical Systems, Vol. 21, No. 2, April 2012

[36] Seon-Bae Kim, Hyejin Park, Seung-Hyun Kim, H. Clyde Wikle, III, Jung-Hyun Park, and Dong-Joo Kim “Comparison of MEMS PZT Cantilevers Based on d31 and d33 Modes for Vibration Energy Harvesting”, Journal Of Microelectromechanical Systems, Vol. 22, No. 1, February 2013

[37] F. Viola, P. Romano, R. Miceli, Rainfall energy harvester, in Materials and Systems for Energy Harvesting Applications, IGI Global, to be pubblished

[38] Benasciutti D. and Moro L. (2010) Harvested power and sensitivity analysis of vibrating shoe-mounted piezoelectric cantilevers. *Smart Material and Structures, vol. 19 115011* doi:10.1088/0964-1726/19/11/115011

[39] Benasciutti D., Moro L., Zelenika S. & Brusa E. (2010) . Vibration energy scavenging via piezoelectric bimorphs of optimized shapes. *Microsyst Technol 16:657–668*, DOI 10.1007/s00542-009-1000-5, Springer-Verlag

[40] Benasciutti D., Moro L. and Gallina M.(2013). On the optimal bending deflection of piezoelectric scavengers. *Journal of Intelligent Material Systems and Structures, vol. 24, no. 5*, pp. 627-639,.

[41] Ala G., Di Piazza M.C., Tine G., Viola F., Vitale G., “Numerical simulation of radiated EMI in 42 V electrical automotive architectures”, IEEE Transactions on Magnetics, 42 (4) , pp. 879-882.

[42] Ala G., Buccheri P.L., Romano P., Viola F., “Finite difference time domain simulation of earth electrodes soil ionisation under lightning surge condition”, IET Science, Measurement and Technology, 2 (3) , pp. 134-145.

[43] Ala G., Silvestre M.L.D., Viola F., Francomano E., “Soil ionization due to high pulse transient currents leaked by earth electrodes”, (2009) Progress In Electromagnetics Research B, (14) , pp. 1-21.

[44] Viola, F., Romano, P., Miceli, R., Contin, A., “Performance of the shape of Partial Discharge signal wireless probes”, International Conference on Power Engineering, Energy and Electrical Drives PP. 1801 – 1806, doi: 10.1109/PowerEng.2013.6635891

[45] Di Silvestre, M.L., Miceli, R., Romano, P., Viola, F., “Simplified hybrid PD model in voids: Pattern validation”, (2013) International Conference on Power Engineering, Energy and Electrical Drives PP. 1807 – 1813, doi: 10.1109/PowerEng.2013.6635892.

[46] Ala, G., Candela, R., Romano, P., Viola, F., Simplified hybrid PD model in voids (2011) SDEMPED 2011 - 8th IEEE Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives PP. 451 - 455, doi: 10.1109/DEMPED.2011.6063662

[47] http://www.mide.com/index.php

[48] http://www.meas-spec.com