Study on Application of Piezoelectric Vibration Energy Harvesters for Powering of Wireless Sensor Nodes in Large Rotary Machine Diagnostic Systems

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ABSTRACT

A condition monitoring of large rotary machines such as turbogenerators in power plants can be simpler when using a distributed measurement system with wireless sensor nodes. The authors propose an alternative solution to a battery-based powering of these sensor nodes – the application of small-size piezoelectric generators, in which energy of machine mechanical vibrations is harvested and converted to electric energy. Experimental studies were conducted for three bending–beam piezogenerators. A maximization of generated electric power was achieved by matching load impedance to piezoelectric element output impedance and designing suitable weighting mass for mechanical resonance. A reduction of power-processing losses was also studied. The operation of the piezoelectric element and the weighting mass setup was investigated in real conditions on a turbogenerator. Generated power levels were compared for three vibration directions and for various locations on the turbogenerator stator.

Keywords: vibration energy harvester, piezogenerator, wireless sensor network, turbogenerator, condition monitoring

1 INTRODUCTION

One of the most important Wireless Sensor Networks (WSNs) applications is on–line monitoring of a technical condition of various machines, buildings and vehicles. In general, the main benefits arising from using condition monitoring systems are increased safety, reduced maintenance costs (higher reliability) and greater productivity. An illustrative example of a machine that should be regularly supervised is a large rotary electric machine such as a turbogenerator in power plant. The condition monitoring of these machines involves mechanical vibration measurement, which enables to detect many possible faults in bearings, rotor and stator windings as well as in stator core plates and teeth.

Systems for turbogenerator condition monitoring together with software diagnostic tools have been developed for several years at the Technical University of Lodz, Department of Microelectronics and Computer Science, in the cooperation with the Institute of Power Engineering in Warsaw. As a part of these studies, a new distributed system for measurement of turbogenerator mechanical vibrations is planned to be built in the form of a WSN with the sensor nodes installed at different locations of turbogenerator stator outer surface. The elimination of cable connections in this system will significantly reduce cost and complexity of system installation and maintenance. Each node will measure mechanical vibrations in three perpendicular directions with the use of MEMS accelerometers. The acquired measurement data will be transmitted via ZigBee radio interface to a central unit for analysis and storage. Wireless sensor nodes will also require autonomous power supply, which motivated the research on vibration energy harvesting.

A battery-based powering of the sensor nodes would bring several limitations - regular service requirement, unreliability at elevated ambient temperatures, risk of explosion after accidental terminal short–circuiting, possible natural environment contamination. The authors consider the alternative solution to batteries, which is based on application of small generators "harvesting" available ambient energy and converting it into electric power. In the considered application, mechanical vibrations propagating toward stator body can be used to generate electric power for the sensor nodes. This approach is expected to be the most efficient since there is neither constant illumination nor significant temperature gradients at the turbogenerator stator. Another possible source of energy to be harvested is an electromagnetic field and both solutions are compared in the paper.

2 EXPERIMENTAL SETUP

The main elements of experimental setup were generators called Vibration Energy Harvesters (VEHs). In general, there are three types of VEHs: electrostatic, electromagnetic and piezoelectric ones [1].

Electrostatic VEHs are variable capacitors in which inertial force acting on a proof mass mounted to one of the capacitor plates performs work against electric field, which increases energy stored in the capacitor. These generators require external voltage source and therefore are not suitable for replacement of batteries.

In electromagnetic VEHs, a harmonic motion of a coil in magnetic field produced by permanent magnets results in induction of alternating electric current. The voltage levels generated by electromagnetic VEHs are typically low and need to be boosted.

Piezoelectric VEHs convert strain energy in piezoelectric material into electric energy by electric charge separation. The piezoelectric method of vibration energy harvesting is considered the most effective (as power level per VEH size unit is compared) [2]. Piezoelectric generators are less expensive and more widely available than electromagnetic ones. Consequently, piezoelectric type of VEH was selected for the main course of further studies.

2.1 Piezoelectric Bending–Beam VEHs

Three different prototype models of piezoelectric VEHs were assembled for the purpose of experimental studies. All of them were based on commercially available piezoceramic benders [3]. Two piezoelectric plate transducers were applied – SMGE40W11T17W from Steiner&Martins, Inc. and EH220-A4-503YB from PiezoSystems, Inc. Both of them are made of PZT material deposited on both sides of a substrate, which is epoxy and brass sheet respectively. The two piezoceramic layers in each transducer are connected in parallel and the polarization vectors point in the same direction.

Two of the piezoelectric VEHs were constructed as a cantilever beam structure with one end of the beam fixed and the other with a weighting mass fastened that can move freely in a direction of external excitation (Fig. 1).

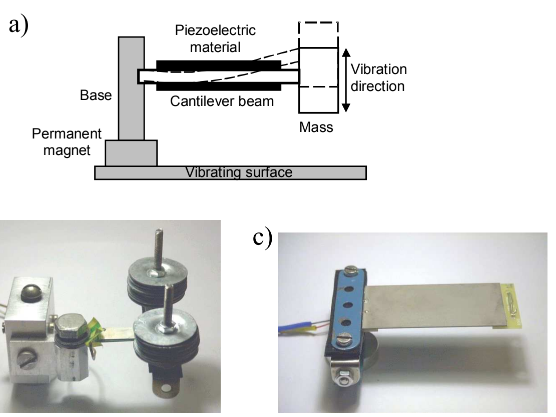

Figure 1: Cantilever bending–beam structure (a) and actual views of the VEHs with SMGE40W11T17W transducer (b) and EH220-A4-503YB transducer (c).

A maximum resonant frequency of the cantilever beam structure is limited by a stiffness and geometry of the bender. That's why, both ends of the EH220-A4-503YB transducer beam were clamped in the third piezoelectric VEH to increase bending stiffness and achieve higher resonant frequency. A weighting mass was placed at the half of the beam length (Fig. 2).

All piezoelectric VEHs were equipped with strong neodymium permanent magnets for quick and firm mounting to a vibrating surface.

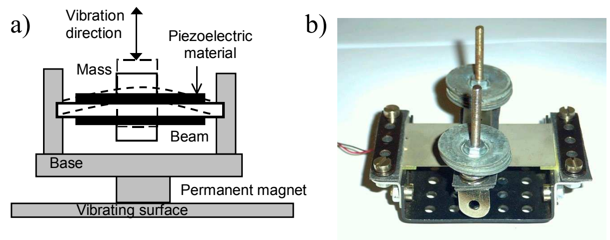

Figure 2: Bending–beam structure with the beam clamped on both ends (a) and actual view of the corresponding VEH with EH220-A4-503YB transducer (b).

2.2 Power–Processing Circuits

The applied power–processing block consisted of an AC–DC converter, a smoothing capacitor and a DC voltage regulator [4]. The AC–DC converter was a full–wave diode bridge with low forward voltage drop and low reverse bias current Schottky diodes. Two types of DC voltage regulators were used – linear 5 V LDO regulator MAX666 by Maxim (Fig. 3a) and switching 3.3 V buck regulator based on LTC1474 from Linear Technologies (Fig. 3b). The first circuit utilized "low–battery" input and output of the regulator to sense voltage at the smoothing capacitor and switch the regulator on or off with the hysteresis 6.6/4.5 V.

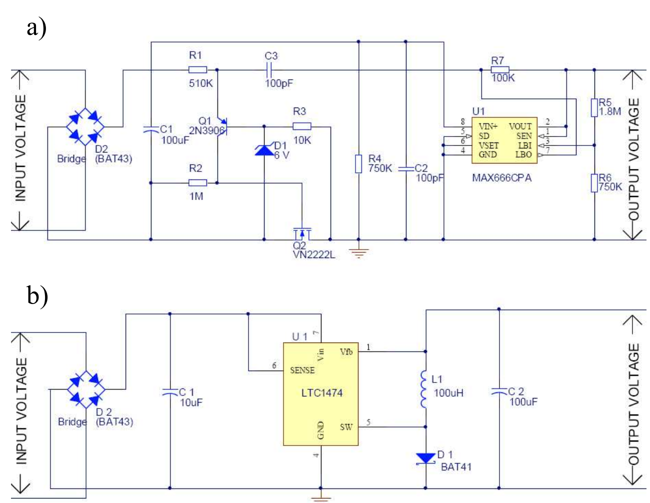

Figure 3: Schematic diagrams of the power–processing blocks with linear (a) and switching regulator (b).

2.3 Alternative Energy Harvesters

In order to assess performance of the studied piezoelectric VEHs, two alternative energy harvesters were tested in the same conditions. The first one was electromagnetic VEH PMG17–100 from Perpetuum Ltd. The resonant frequency of this device is tuned to 100 Hz by the producer. The second energy harvester was simply a

NSTI-Nanotech 2009, www.nsti.org, ISBN 978-1-4398-1782-7 Vol. 1, 2009

high inductance (ca. 1.5 H) coil with ferromagnetic core and it was intended to harvest energy from turbogenerator electromagnetic field instead of harvesting mechanical vibrations. The dimensions of the coil were comparable to the dimensions of the piezoelectric VEHs.

3 RESULTS AND DISCUSSION

The experimental procedure included four steps: matching of a load impedance to piezoelectric VEH output impedance, piezoelectric VEH resonant frequency tuning, evaluation of power–processing block efficiency and VEH output voltage measurements on a turbogenerator.

3.1 Load Impedance Matching

Generated power levels of all the piezoelectric VEHs were measured for various load resistances at a given vibration frequency (Fig. 4). As a result, load resistance values were determined for each piezoelectric VEH at which generated electric power reaches its maximum:

- 55 kΩ for VEH 1 (SMGE40W11T17W) at 100 Hz
- 7.50 kΩ for VEH 2 (EH220-A4-503YB) at 50 Hz
- 7.25 kΩ for VEH 3 (EH220-A4-503YB) at 100 Hz

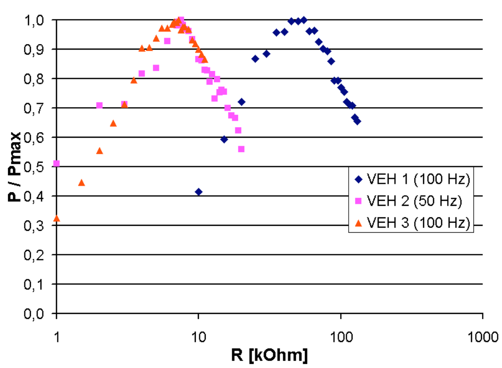

Figure 4: Plots of generated power to maximum generated power ratio versus load resistance.

The above values, except for the second one, agree well with impedances calculated basing on internal capacitances measured for each VEH.

3.2 Resonant Frequency Tuning

Characteristics of generated electric power as a function of vibration frequency were measured (Fig. 5). A vibration frequency at which generated power reaches its maximum for constant vibration acceleration corresponds to mechanical resonance. This frequency was tuned to a desired value by gradual addition of weighting mass. The following optimal mass values were determined:

- m = 132 g for VEH 1 at 100 Hz
- m = 0.4 g for VEH 2 at 50 Hz
- m = 56 g for VEH 3 at 100 Hz

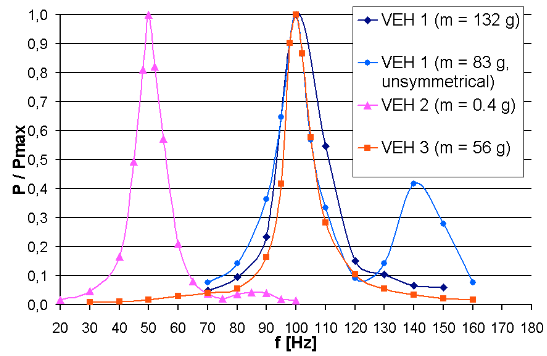

Figure 5: Frequency characteristics of piezoelectric VEHs.

The first and the third VEHs were tuned to 100 Hz, which is the second harmonics of rotor revolution frequency. The second VEH could not be tuned to 100 Hz by adding a weighting mass since its resonant frequency was limited to 54 Hz so it was tuned to 50 Hz.

When the weighting mass distribution was unsymmetrical along a beam axis, a given resonant frequency was achieved for lower total weighting mass than in the symmetrical case. This arises from a superposition of beam bending and torsion when the weighting mass is distributed unsymmetrically. For instance, the optimal unsymmetrical mass value for the first VEH was 83 g and generated power maxima appeared at 100 Hz and 140 Hz. However, the generated power level at 100 Hz was five times lower as compared to the symmetrical case because of a reduced bending force for the lower weighting mass.

3.3 Power–Processing Efficiency

Power–processing efficiency evaluation started with the selection of Schottky diodes for the AC–DC converter. According to the comparative studies, it turned out that BAT43 diodes yielded the lowest power losses from all investigated diodes due to the lowest forward voltage and moderate reverse current.

Next, the power–processing blocks, with the linear and switching voltage regulator respectively, were connected to the first VEH with the load impedance matched. The results (Table 1) showed that the switching regulator ensured a more constant power–processing efficiency for a wide range of processed power levels.

Voltage regulator	Generated power [mW]	Processing efficiency [%]
Linear 5.0 V	1.6	34
	5.0	64
Switching 3.3 V	1.6	53
	5.0	54

Table 1: Power–processing efficiencies.

3.4 Measurements in Real Conditions

Generated power levels were measured for all the examined energy harvesters on 230 MW turbogenerator with rotor revolution frequency of 50 Hz. These values for piezoelectric VEHs were much lower than the power levels obtained in laboratory conditions using 50 Hz or 100 Hz vibration excitation with RMS acceleration of 0.5 $m \cdot s^{-2}$ (Table 2).

Energy harvester	Power generated in laboratory [mW]	Power generated in real conditions [mW]
VEH 1 (piezo)	1.77	0.003 to 0.007
VEH 2 (piezo)	1.36	0.010 to 0.033
VEH 3 (piezo)	0.45	0.005 to 0.015
VEH 4 (electromagnetic)	2.00 (declared value)	1.12
Coil	–	0.11 to 4.84

Table 2: Generated power levels.

A generated power level for the VEHs varied with location by a factor of 2 to 3. The highest harvested power was available close to a turbine. In contrast, a maximum power was harvested from an electromagnetic field of the turbogenerator in the locations opposite to the turbine end. Moreover, the generated power level for the coil harvester was highly dependent on a direction and location.

The VEHs harvested vibrations in radial direction (perpendicular to the rotor axis). For the first VEH, a slightly higher powers were generated in axial and stator tangent directions (up to 16 and 13 µW, respectively).

In a recorded frequency spectrum of turbogenerator vibration acceleration, many harmonics of the fundamental frequency could be observed (Fig. 6a). However, in another turbogenerator the 50 Hz vibration component dominated (Fig. 6b).

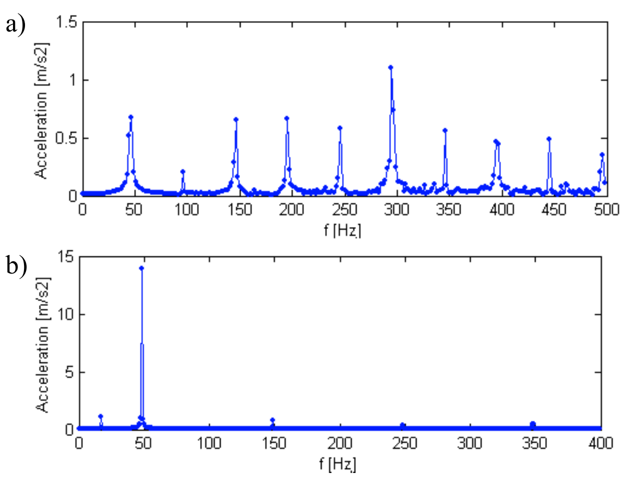

Figure 6: Frequency spectra of turbogenerator vibration acceleration amplitude – radial direction.

The presence of many vibration components was reflected in frequency spectra of generated voltage (Fig. 7). As a result, the previously determined load matching conditions were no longer satisfied.

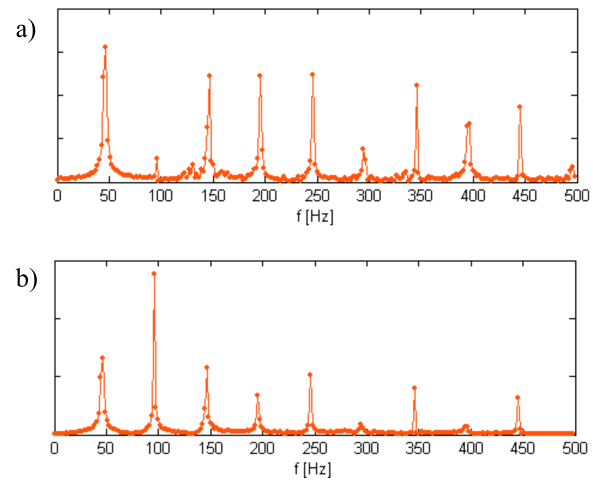

Figure 7: Frequency spectra of generated voltage for the second (a) and the third (b) VEH.

4 CONCLUSIONS

The study confirms that piezoelectric VEHs are able to generate a power similar to that of larger and more expensive electromagnetic harvesters. However, in the considered application, unsatisfactory results were achieved and the piezoelectric VEHs need a further optimization.

In future work, it will be important to select the best vibration frequency component for most turbogenerators, which should be a rotor revolution frequency, and design a VEH with a high Q factor for this component.

Furthermore, a generated power can be significantly increased with the use of nonlinear interface circuits [5]. In order to minimize power–processing losses, application of switching voltage regulators and dynamic load impedance adaptation is advisable.

Finally, a level of generated power will not be high enough for continuous operation of the sensor nodes and it can vary in time at different locations, which all must be taken into account.

REFERENCES

[1] S. Beeby, M. Tudor, N. White, Meas. Sci. Technol., 17, R175–R195, 2006.
[2] S. Roundy et al., Pervasive Computing, 4, 28–36, 2005.
[3] H. Sodano, J. Lloyd, D. Inman, Smart Mater. Struct., 15, 1211-1216, 2006.
[4] G. Ottman, H. Hofmann, G. Lesieutre, Transactions on Power Electronics, 18, 2, 696–703, 2003.
[5] M. Lallart et al., Sensors and Actuators A, 147, 263–272, 2008.