A Rotating Machine Acoustic Emission Monitoring System Powered by Multi-source Energy Harvester

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Abstract

This working paper introduces an multi-source energy harvesting powered acoustic emissions (AE) monitoring system for the applications of rotating machine fault detections. This wireless sensor prototype records the AE signal at approximately 200KHz frequency. It performs fast Fourier transform (FFT) and compares the results with known fault patterns. An energy harvesting solution utilizes vibrational, thermal and light energy as the power supply for the AE wireless sensor node. The multiple-source energy harvester proposed in this work generates 1.56mW from 25-48mg vibration energy and 3.37mW from thermoelectric energy when deployed on the 62^{o}C metal surface of air compressor. This AE wireless sensor prototype combines with the battery-less energy harvesting power supply in order to provide a self-powered health monitoring solution for wide range of rotating machinery.

Keywords

acoustic emissions, energy harvesting, power management, supercapacitor

1 Introduction

In most modern buildings and industries, rotating machines, such as electric motor, pump, turbine and compressor, are widely equipped. In these machinery, gear is an important component and the most common moving part. High reliability is required for long period of time in harsh environment. Unexpected Faults (UFs) of the gear may lead to significant damages of entire machine. If not detected in time, these UFs may lead to substantial repair, labour and downtime costs. Therefore, on-line condition monitoring (OCM) are often used to perform preventive maintenance (PM) in order to effectively diagnose and prevent further development of UFs [2].

The method of Acoustic Emission Monitoring (AEM) has been proposed for PM applications in recent years [4] and [3]. Acoustic Emissions (AE) are the sound waves produced when a surface displacement is created by external stress. For gear fault application, AE transient elastic waves are produced by the interactions of two media of gears in relative motions. Monitoring systems "listen" to AE and perform frequency/time domain signal processing to identify fault "pattern" in the early stage of surface/subsurface crack formation.

The development of wireless sensor networks (WSN) technologies in recent years presents new opportunities for AEM systems [5]. Previously, AEM system is often controlled by programmable logic controller (PLC) and data transmission is via Modbus serial communication. The WSN module, which consists of low cost micro-controller (MCU) and wireless transceiver, provides a significantly more cost effective solution. Another advantage of WSN based AEM system lays in its deployment phase. The battery powered WSN requires minimal cost and expertise during installation process. Due to these advantages, WSN based AEM system has been proposed for infrastructure (bridges and buildings) structural health monitoring applications [9] and [1].

For WSN AEM module, it is possible to power the system with battery. However, this also leads to a bottleneck of WSN development due to the limited battery energy. The WSN based AEM consumes higher power than light/temperature monitoring WSN systems mainly due to the 50mA-100mA current consumption of AE sensors and amplifiers. WSN AEM system is programmed to perform power conservation duty cycling operation, i.e. WSN module alternately switches between high power consumption active mode and low power sleeping mode. It remains in sleeping mode for most of time, leading to substantial energy savings. The duty cycling WSN node will consumes an average of 2mW level power consumption when the duty cycle is set to 1%. When powered from a 3.7V 1000mAh battery, the 2mW ultra-low power WSN system can only achieve approximately 75 days battery lifetime in optimal condition. The battery replacements are expensive and even not feasible when the mote is placed in locations difficult to access.

Energy harvesting technologies provide a possible solution for WSN AEM system. This method "harvests" ambient energy such as vibration [15], thermoelectric [7] and solar/light [13] into electricity to power WSN system. The power management circuits of energy harvester charges the

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supercapacitor to store the harvested energy and discharge it to utilize the energy. The utilization of the "infinite" environmental energy leads to a long lifetime for WSN systems. Multiple sources energy harvesting has been proposed to harvest energy from more than one type of energy in order to maximize the power generation[14].

A new type of machinery preventive maintenance system is proposed in this paper utilizing three technologies: 1) AE sensing, 2) Wireless sensor system, and 3) Energy harvesting. This paper introduces a vibration/thermoelectric/light multi-source energy harvesting powered acoustic emission monitoring system for rotating machinery fault detection application.

The rest of the paper is organized as follows. Section 2 presents the AEM prototype and related signal processing. Section 3 presents the multiple-source energy harvesting system and power management circuits. We present the prototype implementation and the preliminary test results as of August 2013. Section 4 concludes the findings and proposes future work.

2 AEM System

The block diagram of the proposed energy harvesting powered AEM system is shown in Fig. 1. The system consists of: 1) Sensor Layer; 2) DSP & RF Module; 3) Energy Harvesting Module; 4) Expert System.

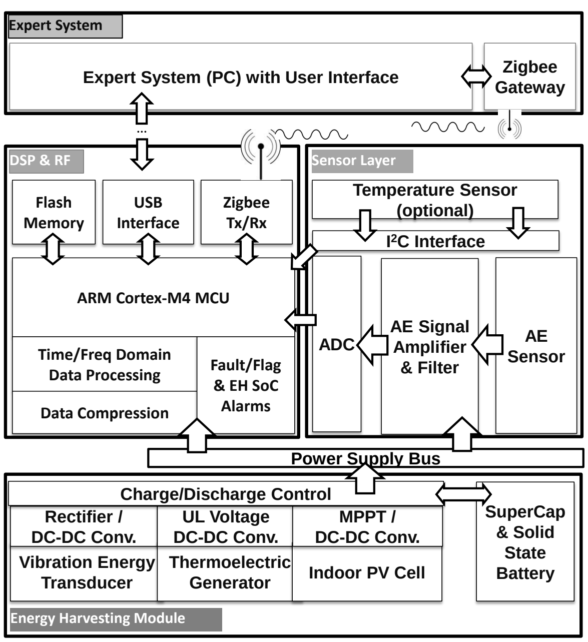

Figure 1. Energy Harvesting Powered Wireless AEM System Architecture

On the sensor layer the AE sensor signals are processed by amplifier, filter and analog to digital converter (ADC). The DSP and RF module consists of ARM Cortex-M4 micro-controller, NXP JN5148 Zigbee wireless transceiver, flash memory and USB interface. The data processing is mainly based on fractional Fourier transform (FRFT). The results are compared with fault patterns to "flag" the possible fault. If the fault "flag" re-appears over a extended period of time, fault alarm will send to the expert system via the wireless communication. Flash memory is used to temporarily store the data in the case of unsuccessful RF data transmission.

The energy harvesting (EH) module includes: 1) rectifier and DC/DC converter for electromagnetic (vibration) energy harvester, 2) ultra-low voltage (UL) DC/DC converter for thermoelectric generator (TEG), 3) maximum power point tracking (MPPT) for indoor photovoltaic cells (PV), 4) super-capacitor energy storage unit (ESU) and 5) charge/discharge control circuit to conditioning the input/output power from ESU. The ESU state of charge (SoC) is sent to MCU to monitor the condition of energy harvester.

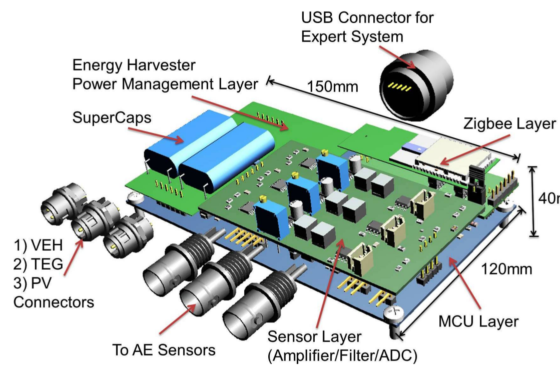

Figure 2. Energy Harvesting Powered Wireless AEM System Prototype 3D Illustration (the protection case is not shown in this illustration)

The 3D drawing of the prototype illustrates the four subsystem layers and the connectors configuration as shown in Fig.2: Energy harvester power management layer, Sensor layer (amplifier/filter/ADC), MCU layer and Zigbee communication layer. Three AE sensors, vibration energy harvester (VEH), thermoelectric energy generator (TEG) and photovoltaic cells (PV) can be connected to this system.

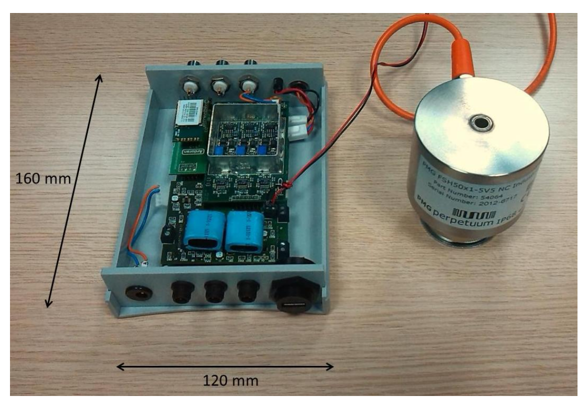

Figure 3. Energy Harvesting Powered Wireless AEM System and Vibration Energy Harvesting Transducer)

The main energy storage unit in this implementation consists of two 5F super-capacitors. The prototype is measured at 160mm×120mm×40mm. The ingress protection rating of the case is IP-54. All subsystems have been prototyped and manufactured as of August 2013. The complete energy harvesting AEM system and a vibration energy harvesting transducer are shown in Fig 3.

The "fault pattern" of gear is the main diagnostic parameter in this on-line preventive maintenance system. Gear testing was conducted to identify the fault patterns in various frequency bandwidths. Fig.4 shows the test set-up of the gear surface/subsurface crack formation experiment conducted in this project.

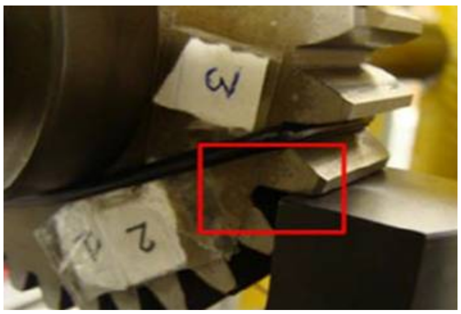

Figure 4. Gear Surface Crack/Wear Acoustic Test Set-up

The area highlighted in Fig.4 is the root circle of a gear where the crack most likely to form. The AE fault pattern tests were conducted with several different types and stages of crack formations.

Fractional Fourier transform (FRFT) method is used in this work to perform time-to-frequency domain transform[6]. Fig.5 shows the detected frequency domain fault pattern at 200KHz when the late stage of the crack formation is scanned with a 150-300KHz filter.

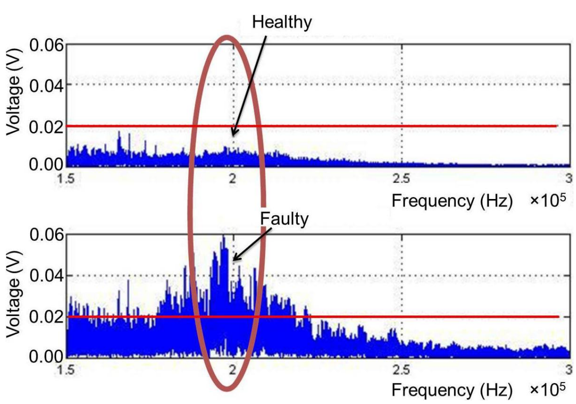

Figure 5. Gear Fault (crack) Pattern in Frequency Domain Analysis 150-300KHz FRFT Results

In the power consumption prospectives, as of August 2013, power consumption simulations have been performed on this device. Based on the components data sheet and subsystem power consumption measurement results, this device is estimated to consume 80-180mW power during "active" mode and 50μW in "sleep" mode. The simulated power consumption of AE WSN mote is summarized in Table.1.

The AE WSN system is performing duty cycling operation in order to achieve lower power consumption.With the sleep mode time set between 1 and 10 minutes, the average power consumption is calculated between 0.22mW to 1.76mW as shown in Table. 1.

AE Power Consumption	Power (mW)	Time (Sec)	Energy (mJ)
Sleep Mode	0.047	60.00	2.820
Data ACQ (3 AE Sensors)	188.1	0.020	3.760
Data FRFT	76.26	0.920	70.16
Diagnosis Algorithm	86.16	0.210	18.09
RF Transmission	61.38	0.220	13.50
Duty Cycled Average (1min T_S)	1.760	61.37	108.3
Duty Cycled Average (10min T_S)	0.220	601.3	133.7

Table 1. Power Consumption of AE WSN Mote (T_S : sleep mode time)

3 Multiple Source Energy Harvesting

In order to achieve "power autonomous" operation of AE sensor system, energy harvesting is proposed to scavenge ambient energy and convert the harvested energy into usable form. On-site experiments had been carried out to investigate the available ambient energy sources on an industrial cold store facility. The mechanical vibration energy and surface temperatures on various positions of two rotary screw air compressors have been measured as shown in Fig.6.

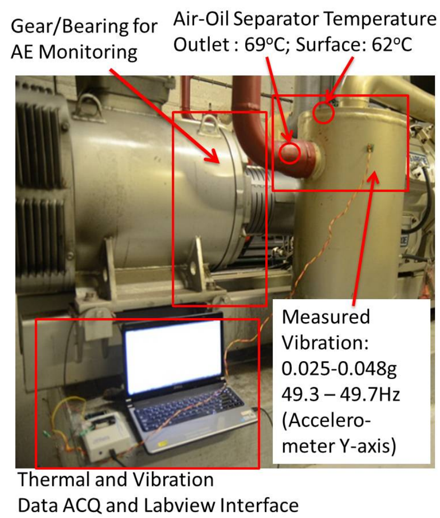

Figure 6. Energy Harvesting Source Characterizations on a Rotary Screw Air Compressor

The mechanical room where the air compressors are located has weak light intensity at approximately 200 lux. The main energy harvesting source will be the vibrational and thermal energy from the machine. A maximum of 0.048g on the vertical direction vibration has been detected in addition to the 60 - 70 ^{o}C surface temperature on the air compressor (sensors placed near the air-oil separator air outlet).

Thermoelectric energy harvesting is thus proposed in this work due to the measured high temperature. Thermoelectric generator is a device that utilizes Seebeck effect which directly converts temperature difference into electricity without moving part[12]. One low cost Bi_2Te_3 thermo-couple only generates small voltage difference (1mV) when 5^oC temperature difference is applied between the "hot" and "cold" sides of TEG. An array of thermo-couples are used to form a TEG module which normally consists of several hundreds thermo-couples in order to obtain higher and "usable" voltage.

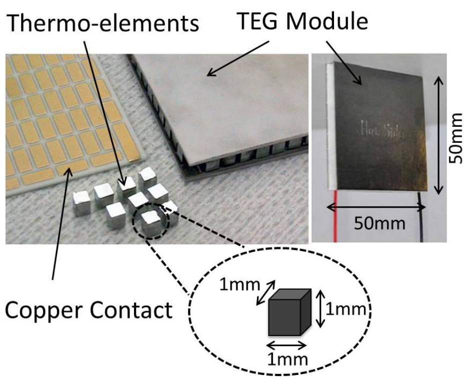

Figure 7. Thermoelectric Generator (TEG) Module

Fig.7 shows the structure of a TEG module and its P/N thermo-element. This module has a 16 row × 16 column configuration, one thermo-couple has been removed in order to connect the terminal leads. Thus, 255 thermo-couples forms this TEG, connected via copper contacts. Two layers of ceramic substrate are used to support the thero-elements. This TEG is tested with hot side temperature ranging from 50^oC to 80^oC for this application. Heat sink (same to CPU heat sink without cooling fan) is mounted on the cold side of TEG. TEG voltage and power characterization results are summarized in Table.2.

Table 2. TEG Characterizations Results at Matched Load (Laboratory Environment: 20^oC room temperature, minimal air flow)

Heat Source Temp (^oC)	50	60	70	80
Module Temp Diff. ΔT (^oC)	2.5	4.0	5.5	7.5
Measured Voltage (V)	0.212	0.336	0.464	0.632
Measured Max. Power (mW)	1.384	3.544	6.704	12.46

Due to the strong vibration amplitude (25mg to 48mg) measured on the air compressor, vibration energy harvesting is proposed. A vibration energy transducer module (PMG FSH) manufactured by Perpetuum [11], [8] is used in this work. Detailed parameters related to the energy generation of this transducer can be found in [11]. AC-DC rectifier and DC-DC converter are integrated in the Perpetuum transducer, a regulated 5V output voltage is generated at the output.

Although the light intensity in this application is limited (<200lux), light energy is the most ubiquitous type of ambient energy in general. For other applications, higher indoor light intensity (500lux level) has been measured [13]. For outdoor applications, such as bridge structure AE monitoring [1], photovoltaic energy harvesting is particularly important. Photovoltaic energy harvesting is, thus, also proposed in this design.

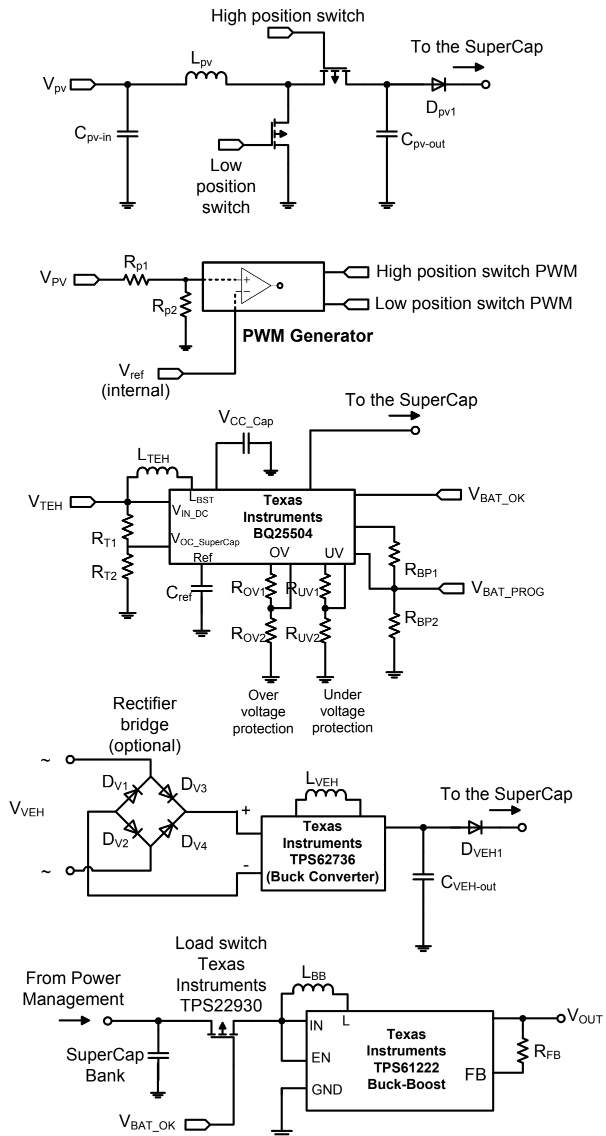

Figure 8. Schematics of Energy Harvester Power Management Circuit

Super-capacitor type of energy storage unit is used in this design for its long lifetime (>10 years) and large number of recharge cycles (>100,000 times). In addition to the long lifetime characteristics, this capacitive energy storage only requires a simple charge/discharge control circuit. The power management circuit of the proposed multi-source energy harvester is shown in Fig. 8.

The power management circuit consists of two types of conditioning circuit: 1) input power management which converts the harvested energy from energy harvesting transducer to usable form and charges the energy into the super-capacitor bank. 2) output power management which extracts and regulates the super-capacitor stored energy to a regulated 5V output for the AE WSN system load.

For thermoelectric energy harvesting, the power management circuit is developed based on Texas Instruments BQ25504 ultra-low voltage buck-boost converter. This converter steps up the <0.2V output voltage of TEG to charge the super-capacitor with $> 60\%$ conversion efficiency. A maximum power point tracking (MPPT) function for thermoelectric generator is included in this design. By setting both R_{T1} and R_{T2} to $1\text{M}\Omega$, the operating voltage of the TEG is set to 50% of the open circuit voltage V_{OC} which is close to the maximum power point for thermoelectric generator. R_{OV} and R_{UV} resistors array is used to perform the over-voltage (OV) and under-voltage (UV) protection. The OV voltage threshold is set to 5V which is the voltage rating of the super-capacitor. The UV voltage threshold is set to 2.2V with hysteresis preventing the energy storage unit from over discharge. This function, however, is not necessary due the energy storage unit used in this application is super-capacitor which does not require under voltage protection. Thus, the 2.2V minimal UV voltage of TI BQ25504 is selected. Once the voltage on the V_{CC} capacitor $V_{CC-Cap}$is higher than 1.8V, the system starts to operate and charges the super-capacitor bank towards 5V maximum voltage. The "battery OK" signal of TI BQ25504 indicates the voltage of the super-capacitor is within a pre-programmed voltage range and can be used for the load. This voltage range is programmed by the R_{BP} resistors array. This voltage range is set to the maximum range, i.e. between 2.3V and 5.0V, in this application for maximum energy extraction from the super-capacitor. The "battery OK" signal V_{BAT-OK} is used to control the load switch TI TPS22930. Once the super-capacitor voltage is within the 2.3V and 5.0V, V_{BAT-OK} is set high to enable the output voltage regulator TI TPS61222 buck-boost converter.

For vibration energy harvesting, the power management circuit consists of a full bridge rectifier and a buck converter. The AC-DC rectifier is, however, optional in this application since the PMG FSH vibration energy harvesting transducer integrated an AC-DC rectifier. TI TPS62736 buck converter is used in order to maintain the transducer voltage to 5.0V instead of been pull-down to the super-capacitor voltage. This function enables the maximum power operation of the transducer.

For photovoltaic energy harvesting, the power management circuit is designed based on a discrete component based boost converter. The high/low position switches of this boost converter are controlled by a PWM generator. The PWM generator is programmed by a pair of comparators which only switch on the boost converter when the input capacitor voltage C_{pv-in} is within the pre-set maximum power point voltages. This method enables maximum power point tracking (MPPT) with low power consumption.

Both the vibration and photovoltaic harvested energy is used to charge the common super-capacitor bank. Same to the thermoelectric energy harvesting power management, the "battery OK" signal on the TI BQ25504 converter is also used to active the output voltage regulator for these two type of energy harvesting power management circuits. In addition to the energy harvesting type power management, a 24V to 5V DC-DC converter is adopted in this circuit for standard industrial 24V power supply in case that no energy harvesting source is available.

The multi-source energy harvester prototype is implemented. The complete energy harvesting power management prototype is shown in Fig.9. In this prototype, two 5F super-capacitors are used as the main energy storage unit.

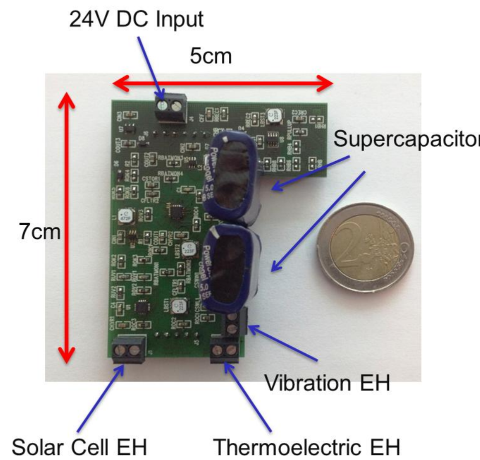

Figure 9. Energy Harvesting Sub-system Prototype

On-site experiments have been conducted to verify the design. The prototype device is deployed on the air compressor unit in the cold store facility. The super-capacitor voltage and charge time are measured to calculate the harvested power and energy. The average harvested power P_{avg} can be derived from the super-capacitor energy E_{SC} and charge time T_{chrg} as,

$$P_{avg} = \frac{E_{SC}}{T_{chrg}} = \frac{C_{SC} \cdot (V_{final}^2 - V_{init}^2)}{2 \cdot T_{chrg}} \quad (1)$$

where C_{SC} is the super-capacitor capacitance, V_{final} and V_{init} are the final voltage and initial voltage of the super-capacitor.

In addition to the energy harvesting prototypes, accelerometer and thermo-couples are used to measure the temperature and vibration at various part of the air compressor. The data is recorded using a portable Picolog-1000 data acquisition system with labview interface. The purpose of this deployment study is to determine the most suitable deployment position of energy harvester on the machines. The optimal position where energy harvesters can be deployed is the air-oil separator air outlet where shows both high temperature and high level of vibration.

In this application, due to the low light intensity in the mechanical room, the photovoltaic energy harvesting is not used in this experiment. The super-capacitor charging experiments were conducted on TEG and vibration energy harvester. The results are shown in Fig.10.

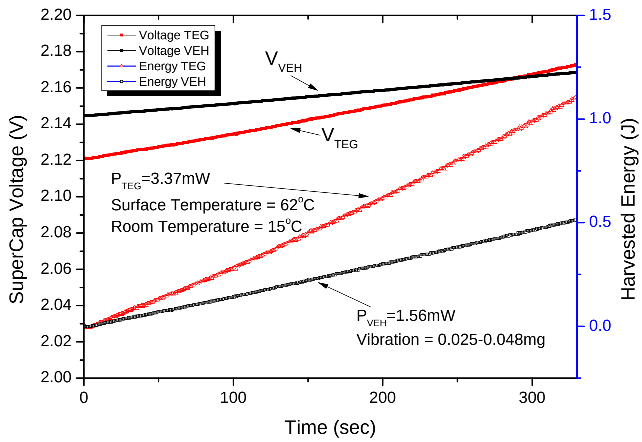

Figure 10. VEH and TEG Energy Harvesters Supercapacitor Charging Experiments

The harvested thermoelectric energy is calculated based on the voltage change on the super-capacitor at 1.01J within 300 seconds. The average harvested power of TEG is calculated at 3.37mW. The charge experiment was also conducted with different capacitors, the harvested power remains the same value. The vibration of the air compressor tested in this experiment varies significantly due to its different operation modes, 25-48mg magnitude at 49.3-49.7Hz frequency is measured. The harvested energy is measured at 0.47J in 300 seconds. The harvested vibrational power is 1.56mW on average during the charging process. Whilst the air compressor is operational, the total energy harvested power is calculated at 4.93mW.

The harvested power is sufficient to power AE WSN module to operate with 1 minute measurement intervals (1.76mW in Table.1). Based on the duty cycle power consumption data of the AE WSN system, the multi-source energy harvester supplies enough power to perform fault detection every 20 seconds.

4 CONCLUSIONS

This working paper presents a multi-source energy harvesting powered acoustic emission monitoring wireless sensor node. This prototype device utilizes AE sensors to perform fault detection on rotating machines. It demonstrates the capability to identify gear crack formation by conducting 200KHz high frequency acoustic monitoring.

An energy harvesting power management sub-system has been developed in this work in order to harvest thermoelectric, vibrational and photovoltaic energy. The complete energy harvesting solution with super-capacitor type energy storage unit has been deployed in real-world condition. When the proposed energy harvesting sub-system is deployed on an air compressor in a large scale cold store facility, the energy harvesting sub-system can harvest 3.37mW from wasted heat (62^oC surface temperature in 15^oC room temperature condition) and 1.56mW from machine vibration (25-48mg magnitude at 49.3-49.7Hz frequency). In total, 4.93mW is generated from the multi-source energy harvesting subsystem when the air compressor is operational. Based on the power consumption simulation of the AE system, the harvested power is sufficient to conduct AE fault detection every 20 seconds.

As of August 2013, all subsystems of the AE WSN have been developed and prototyped. The future work is the system level experiment in real-world condition in order to verify the commercial value of this wireless AE monitoring solution.

5 Acknowledgments

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