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Thermal Energy Harvesting based Novel Wireless Sensor Node with Wired Measurement for Condition Monitoring of Gearbox

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Abstract: during operation processes, industrial rotating machines revolve at variable speed under different loads. Under such operating conditions a heat would be generated within the internal components. Yet, temperature may increase within the machines when a fault is developing inside them. Therefore, the temperature of machines can be used effectively to monitor the condition of industrial equipment. This comparative study investigates the use of a novel wireless temperature node and compares the results obtained by wired measurement one. Both nodes are used to monitor the condition a gearbox transmission system under different operating circumstances. That is, the wireless temperature node was fabricated with a novel feature in that it is supplied by a thermoelectric generator module. The module is mounted on the gearbox without the need of using a wired power source or the requirement for recharging, or changing, batteries. Data collected by the node is transferred via a Low Energy Bluetooth and received by CC2540. The collected data is then analysed using a portable monitoring device, such as a PC. Results obtained show that the system can provides reliable monitoring information about the temperature of the monitored gearboxes. Experiments performed demonstrate an outstanding performance of the proposed system which make it suitable for wireless and wired condition monitoring purposes.

Keywords: (energy harvesting, wireless sensor networks, condition monitoring, temperature)

Introduction

Maintenance has become increasingly important to the industrial automated manufacturing processes. Meanwhile, the investment on maintenance has grown quickly with the increasing complexity of machines. Temperature monitoring is one of the most commonly and enormously known monitoring techniques used in the industrial machines. It is widely utilized for mechanical and electric machines. It also provides useful monitoring information about the condition of the components in machines. The gearbox is one of the most important components in the manufacturing. The maintenance cost for the gearbox is very high compared to other high failure rate components such as electric and hydraulic systems. With high and variable rotating speed under time varying load conditions, this bringing great challenges to the monitoring the conditions of gearboxes [1-3]. Cost performance is another factor that should be taken in to account in gearbox condition monitoring. Temperature is an important health indicator of mechanical equipment such as gearboxes [4, 5].

Thermoelectric modules are significant alternative to heat engines in the harvesting of waste heat. Precisely, temperature difference is used in thermoelectric systems based on micro converters exploiting Seebeck effects which are widely known as thermoelectric generators (TEGs). Many applications have been used with TEGs such as structural health monitoring applications [6-9].

The wireless sensor networks (WSN) are becoming widely adopted for many applications including complicated tasks like building energy management. However, one major concern for WSN technology is the short lifetime and high maintenance cost due to the limited battery energy. As lower power products have been used in WSN, energy harvesting technologies, due to their own characteristics, attract more and more attention in this area. Therefore, one of the solutions is to harvest ambient energy, which is then rectified to power the WSN [10,11].

Nowadays, smartphones employ major market of mobile phones than traditional cell phones. Smartphones with the development of wireless transmission technology, the researches on health management, telecommunication and monitoring of physiological signals have been important topics [12,13].

There are number of wireless protocols which can be utilised to establish a wireless sensor networks (WSN). Protocols like WiFi-HaLow, Bluetooth low energy (BLE), ZigBee and Thread are more suitable for long-term non-critical CM battery powered nodes due to inherent merits like low cost, self-organising network, and low power consumption. WirelessHART and ISA100.11a provide more reliable and robust performance but their solutions are usually more expensive, thus they are more suitable for strict industrial control applications [12].

It is particularly suitable for those devices that need transfer small quantity of data and within relatively short range such as medical instruments, health management devices and remote controllers. BLE technology can remove the inconvenience of wired transmission and eliminate the disadvantage of high power consumption in ordinary wireless transmission. In addition, more and more smartphones gain support for BLE, the possibilities of using the technology for new types of applications increase. In addition, WSN node appropriated for using in ultra-low power consumption and energy harvesting support has been developed for the purposes of environmental monitoring [11]-[14,15]

System Design

The block diagram of TEG powered sensor node is shown in Fig. 1, which includes a thermal energy harvester a DC-DC converter for boosting the voltage, a wireless sensor node for measuring temperature and transmitting data and received data by USB module, then monitored using portable monitoring devices, such as PC or smartphone. They will be introduced separately in the following four sub sections.

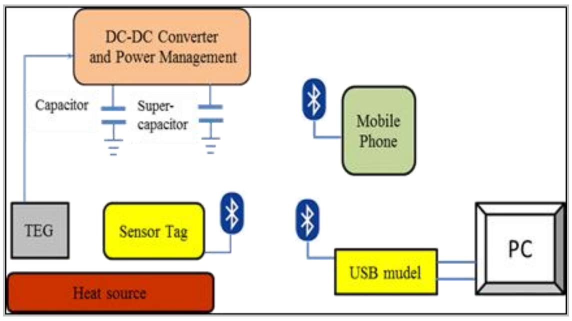

Fig. 1: Block diagram of TEG power sensor node

A. Thermal Energy Harvesting Generator Design

The thermal design is shown in Fig. 2; which consists of: TEG thermal insulation material, a heat sink, and two pieces of thin aluminium; the aluminium plates have been chosen due to the large thermal conductivity. One piece is to work as a heat collector for hot side, while the other one acts as a heat spreader for cold side. The design was built by using a commercially available TE module CP85438 [20]. The TEG is sandwiched between the two pieces of aluminium. Note that, some thermal insulation materials are stuffed between the two pieces of aluminium plates to reduce the heat transmission through the air flow from hot side to the cold side. A thermal insulating material, (thermal heat sink transfer double side adhesive) is designed to maintain temperature difference between hot and cold sides of TEG. Also, another insulation material is designed to surround the TEG module. It has been worked in the thermal design to isolate the heat source from the heat sink. This is due to the fact that the heat source is close to the heat sink, so that is to reduce the heat transfer capability of the heat sink.

The heat sink plays an important role in the thermal energy harvester to maintain a temperature difference by radiating the heat on the code side of the TEG module efficiently to the surrounding air. Here a medium size heat sink with thermal resistance of 1.5 °C /W has been used.

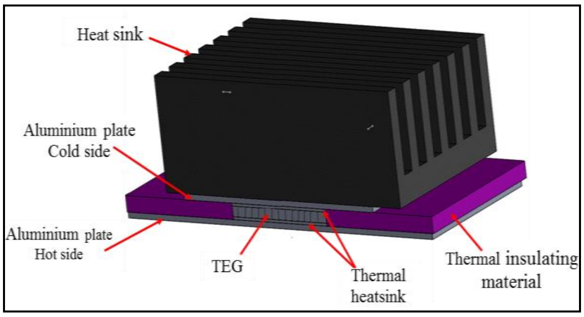

Fig. 2: Structure of the TEG Design

B. Wireless Temperature Node

To measure gearbox temperature, an integrated wireless sensor node named Sensor Tag is employed. As shown in Fig. 3, this compact sensor node integrates 10 low-power MEMS sensors and a two core BLE microcontroller CC2650 [21]. Two temperature sensors are available on the node with one for measuring object temperature and other for ambient temperature. Another benefit of this module is that its programs are open source, which enables to customize the data acquisition and embed intelligent signal processing algorithms on it.

The sensor Tag is specially designed for low power consumption applications and can be supplied by a coin battery [22,23]. Here, the coin battery is not used; instead the sensor tag is powered by the energy harvested from waste heat in order to avoid the inconvenience of changing the batteries during the lifetime of the system.

Fig. 3, Sensor tag CC2650K

C.USB Module

The The CC2540 USB evaluation module kit as shown in Fig. 4 contains one Bluetooth low energy USB dongle. The dongle can be used to enable Bluetooth low energy on our PC. The CC2540 combines an excellent RF transceiver with an industry- standard enhanced 8051 MCU, in system programmable flash memory and 8KB RAM. It is selected on the USB because it suitable for system where very low power consumption is required. It also very low power sleep modes are available and low cost [16],[20,21].

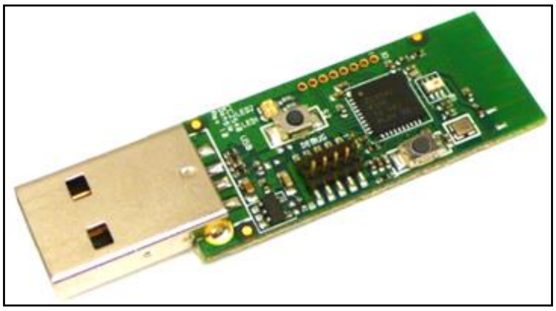

Fig. 4: The USB module.

The Experimental work

A. Performance Analysis on Gearbox

To evaluate the system to power up sensor node for condition monitoring, it is into a gearbox as shown in Fig. 5. The gearbox of test rig consists of three main parts: 15 KW three phase AC induction motor, two gearboxes connected back to back via flexible coupling and DC motor working as load. Therefore, to simulate a variable loads and variable speed operating conditions of common industrial machine the tests were carried out based on changing the AC motor speed while a fixed load applied. The test is designed to evaluate the transfer efficiency of the TE module [17-19].

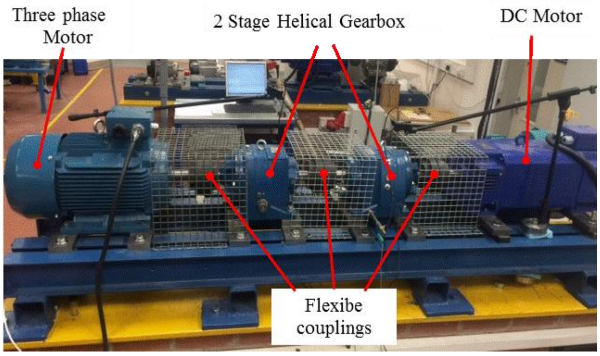

Fig. 5: The Test Rig

The TEG module is attached into the body of the gearbox by clamping it properly on vertical position as shown in Fig. 6. The body heat of the gearbox will be collected by the TEG module and converted to electricity to power the sensor tag. Meanwhile the working condition of the TEG module is monitored by an external data acquisition system to evaluate its performance. The monitoring parameter includes: temperature on the hot and cold side of the TEG module, open circuit voltage of the TEG module and its current over a 1 Ω resistor. Note that, the open circuit voltage and current are measured alternatively by using a relay. The time interval for these measurements is set as 6s.

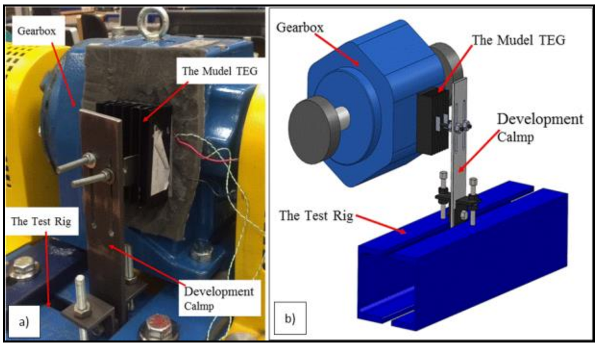

Fig. 6: The module TEG attached the gearbox a) picture of the module with gearbox, b) illustrated the development clamp in sold model

Results and Discussion

To evaluate the performance of the TEG module, set of comparison tests using Gearbox Test Rig were performed. Particularly, healthy gearbox operation condition and abnormal operation, i.e. low oil level with 40% tooth breakage as shown in Fig. 7. The AC motor is operated for one hour at the full speed (100% speed) under 70% of the full load. The readings from TEG module, including temperature, open circuit voltage and power over 1Ω resistor, are obtained by a data acquisition system and stored on a portable PC for further analysis. Fig. 8 represents the TEG module related readings during two sets of different test cases.

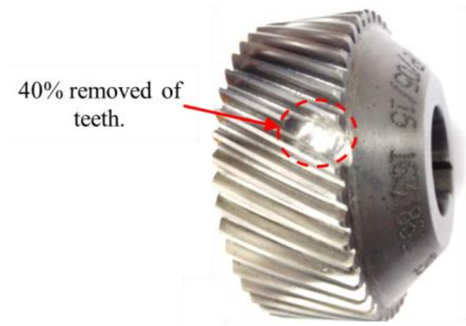

Fig. 7: Tooth breakage

It can be seen that both the hot side temperature T_h and cold side T_c of the TEG module under abnormal operation is higher than those of the healthy gearbox. This is reasonable since more heat is generated when gearbox under abnormal operation conditions. A temperature difference ΔT of around 12°C is maintained between the hot and cold sides. The ΔT of the abnormal operation case is higher than that of the healthy case, as indicated in Fig. 8 (a,b,c).

An open circuit ranging from 140 mV to 175 mV is generated from the TEG module, represented in Fig. 8 (d), which is sufficient for the input voltage requirement of the DC/DC booster circuit. By measuring the voltage of 1

Ω resistor, the power consumption for this resistor, shown in Fig. 8 (e), indicates the power output capability of the TEG module ranging from 2mW to 5mV. It can be seen that the power consumed under abnormal operation case is higher than that of the healthy operation, as clear from Fig. 8 (e).

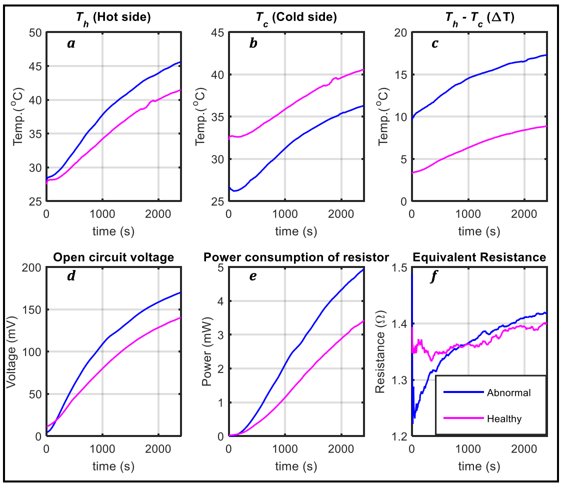

Fig. 8: TEG module related readings, including temperature, open circuit voltage and power over 1Ω resistor

Apart from temperature difference on its two sides, the power output capability of the TEG is also affected by the Seebeck coefficient, which is influenced by the temperature. Due to this phenomenon of the material, the internal resistance of the TEG module also changes with the temperature. By using the open circuit voltage and current over 1 Ω resistor, the equivalent resistance for the TEG module is computed and represented in Fig. 8 (f). A resistance difference of about 0.1 Ω can be observed for these two speed conditions. The results show that the resistance of the abnormal operation test is a bit higher than that of the health condition. This indicates that the internal resistance of the TEG module drops with the increase of the temperature.

WSN node described in this paper is designed for use in the field conditions to monitor industrial parameters as represented in Fig. 9. A super-capacitor is utilized as the main power source of WSN node. That is when there is no energy harvesting or if it is not sufficient for the continuous operation, the super capacitor would then supply the node. It also accumulates energy for a relative long time and then provides power to the sensor node for short period; during which signal is collected and transmitted to the central device. More details about the analysis and application of super-capacitor in WSN can be found in [25].

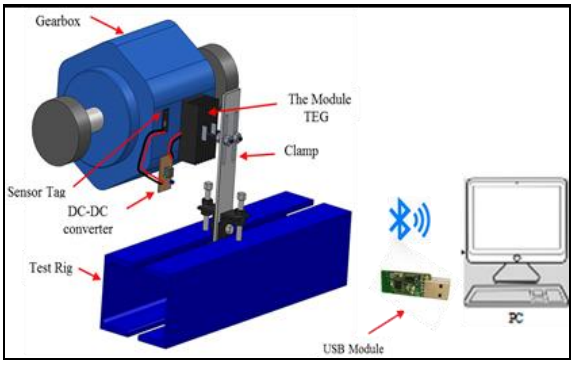

Fig. 9: The test system

By running the gearbox at 100% speed for two hours, the super capacitor can be fully charged, particularly is up to about 5.2V. By connecting the sensor tag to a DC-DC converter, the sensor information on the sensor tag CC2650 can be transferred via the Bluetooth low energy, and received By USB module CC2540. Signals are then monitored and analyzed using portable monitoring devices such as a PC as shown in Fig. 9.

The acquired signals from both TEG and wired sensor are represented in Fig10.

Where Fig. 10 (a) represents the results of temperature measurements obtained from the thermal designed system TEG. It shows changes of the rig gearbox temperature during the run. As clear from the figure, it represents a smooth and uninterrupted data. While Fig 10 (b) shows the wired signal without filtering.

Both signals are superimposed in Fig. 10 (c) for better comparison and visualization. Though small differences in the two signals due to the noise from the wired signal, yet the difference is still acceptable for condition monitoring and diagnosis. Reasonably, TEG wireless system can provide accurate results with less noise and lower power requirements. It can be used effectively for gearbox monitoring by efficiently using energy harvesting technique.

Conclusion

Dependent about the experimental investigation results, it is viable to harvest thermo energy of a machine to power up the wireless temperature node and use to monitor the heath and performance of the machine. Also the comparison study of thermal energy harvesting system has shown a slight different in the data of the different measurement, which leads following conclusion remarks:

- Thermoelectric generator (TEG) has been employed as the energy harvesting source to power up the wireless sensor node for condition monitoring. It can convert the widely available waste heat from machines to electrical energy. Meanwhile, its conversion efficiency is not high.
- Bluetooth Low Energy is employed as the wireless transmission protocol due to its low power consumption and it's widely availability on current portable smart phones and tablets. Third, the new generation low power consumption SOC CC2650 is selected on the sensor node because it integrates one processor for data acquisition and signal processing and also a specific processor for BLE communication.

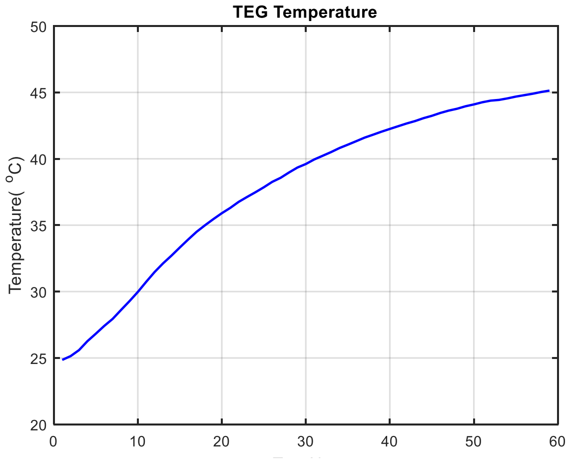

Fig. 10 (a): Results from the thermal design system

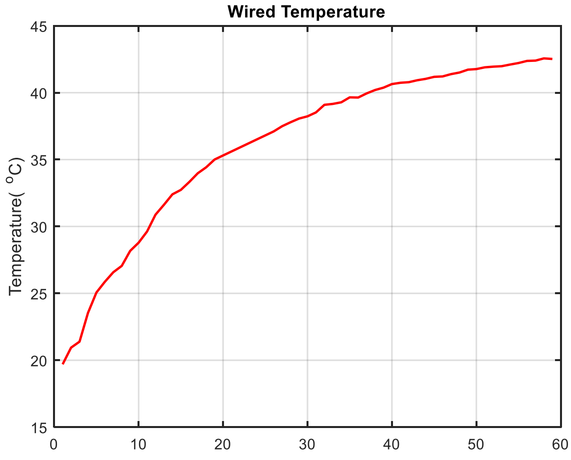

Fig. 10 (b): Results from wired signal

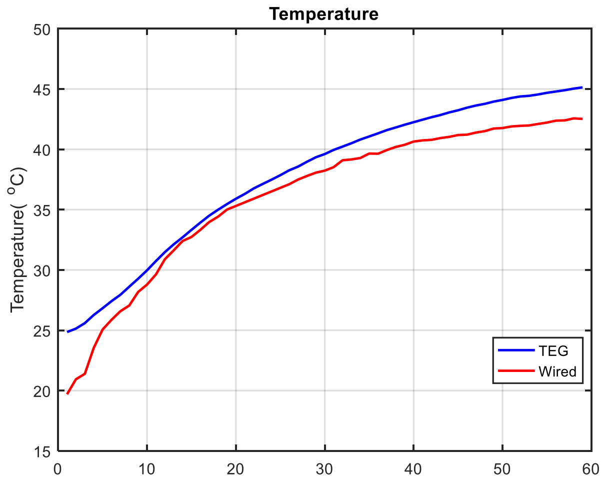

Fig. 10 (c): Comparison results between wired signal and TEG system

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