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Energy harvesting in high voltage measuring techniques

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Abstract. The paper discusses selected problems related to application of energy harvesting (that is, generating electricity from surplus energy present in the environment) to supply autonomous ultra-low-power measurement systems applicable in high voltage engineering. As a practical example of such implementation a laboratory model of a remote temperature sensor is presented, which is self-powered by heat generated in a current-carrying busbar in HV-switchgear. Presented system exploits a thermoelectric harvester based on a passively cooled Peltier module supplying micro-power low-voltage dc-dc converter driving energy-efficient temperature sensor, microcontroller and a fibre-optic transmitter. Performance of the model in laboratory simulated conditions are presented and discussed.

1. Introduction

Endless supply of energy and perpetual power has been a pipe dream of philosophers and engineers manifested in *perpetuum mobile* conception. Perpetual motion machine working indefinitely without any energy source cannot be unfortunately made as it violates the fundamental thermodynamic laws of contemporary physics. However, electronic instruments which live on extracting energy from seemingly perpetual environmental sources and converting it into electricity do actually already exist.

Energy, in various forms – thermal, light, mechanical, electromagnetic (e-m) radiation – is present in our direct surrounding. However, depending on the source, energy density and instantaneous power may be too small making direct supply of technical appliances impossible, especially after additional conversion to electrical energy. Energy harvesting (termed also as *energy scavenging* or *power harvesting*) is an innovative scientific and industrial trend, relaying on extracting environmental energy in small chunks from the direct neighbourhood of the appliance, converting it into electricity and storing it for a discontinuous use. The concept behind this approach is to secure energy self-sufficiency for ultra-low power microelectronic appliances and sensor devices, working in intermittent mode of operation without access to a traditional power network or any kind of replaceable storage battery. Alternative ambient energy sources used in power harvesting are either renewable (like outdoor light, air or water movement) or are related to manmade derivative power sources, from which a surplus energy, dissipated into the environment, is drawn (like indoor artificial light, exhaust heat, mechanical vibrations, electric and magnetic fields, forced fluid and air flow, e-m waves etc.). Selection of a particular environmental energy source is thus dictated by its accessibility in the surrounding area of a supplied apparatus, energy conversion strategy and a required power density.

Energy scavenging provides thus access to energy available locally in practically unrestrained amount but at low or very low momentary power and makes devices totally autonomous, in terms of control and supply. When combined with short range, low power wireless communication and mesh networking it allows to give up structural and power electric wiring, makes sensor systems more flexible and fault tolerant, enhances operation safety, and makes logistics much simpler. Autonomous sensors fitted with power harvesters hardly require servicing, which is a valuable feature especially in monitoring of areas or processes to which access cannot be restricted or which cannot be stopped. Battery-less supply is thus predisposed for electronic sensor systems installed in remote, difficult to reach or hazardous locations, where other categories of electrical supply are inviable or unmanageable. Current trend in construction of energy harvesters is to utilize purely "material" energy conversion by making use of physical phenomena, which yield potential difference. In many cases such generated voltage not directly available for electronics supply or a source-load impedance mismatch is present thus a converter is another vital part of almost every energy scavenger. And as energy accessible from environmental sources is recurring, instable or at low power a harvester must also be equipped with a kind of energy storage arrangement. It must be thus emphasized that energy harvesting does not assert non-interruptible or robust energy supply and therefore, electrical devices supplied by this method must be designed and adapted for irregular operation with unpredictably long out-of-supply intervals. Harvester-supplied device operates thus totally randomly and starts functioning only when the amount of accumulated electrical energy is sufficient for commencement and accomplishment of its task and then it goes into deep sleep state, according to a recurring scheme snooze-on-snooze.

Energy harvesting is currently an excitable subject matter in science and engineering. Extensive reviews on energy harvesting and related topics have been already presented by many authors: Matiko *at al.* discussed current trends in application of energy harvesting in buildings [1], Harne and Wang examined current research in vibration energy harvesting using bistable systems [2], Davidson and Mo considered energy harvesting schemes in structural health monitoring [3], Elvin and Erturk collected advances in energy harvesting methods [4] while Tan presented efforts to design, analyze and implement energy harvesting in autonomous sensor systems [5] – just to name a few.

Energy harvesting is also gradually finding its application in high voltage (HV) engineering, although such efforts are not so numerous as it may appear feasible. Energy harvesting seems to be especially suitable for supplying sensors and measuring devices installed in HV-biased locations, where access and servicing is limited only to occasional situations when HV is off. Zangl *at al.* presented an elegant approach to construct autonomous on-line monitoring network for HV overhead power lines in which sensor nodes, mounted directly on HV conductor cables were supplied by capacitive dividers deriving power from the electric field provided by the HV line itself. At 150 kV 50 Hz AC such power harvesting nodes were capable of delivering approximately 370 mW [6]. Guo *et al.* have extended Zangl's idea by simulating performance of the capacitive harvesting device up to 270 kV and also proposed a linear harvester design intended for HV DC lines, relaying on small winged rectangular winding structure propelled by wind to swirl around the HV conductor line and produce electric power due to electro-magnetic induction in the static magnetic field emanated from the HV DC line. A hypothetical, simulated average power output of such device at 2000 A and 7 m/s wind speed was 1 mW, which was enough to trigger XBee RF wireless radio every 15 min [7]. Zhue *et al.* simulated energy harvesting from electric filed in HV AC substations by means of a large electrode located close to the ground and electromechanical synchronous switching circuit [8]. Roscoe and Judd experimented with harvesting power from ambient AC magnetic field near safely accessible HV appliances (transformers, post insulators, disconnectors, wall bushings, or circuit breakers) located in HV substations, showing that 300 μW may be harvested from 50 Hz magnetic flux density of 18 μT [9]. mNODE (Micropelt) is a commercially available remote temperature sensor powered by inductive energy harvester, converting stray magnetic fields nearby electrical infrastructure elements (like current busbars or power distribution arrangements) into electricity. mNODE is claimed to start its operation at 50 A, is sized 40×40×26 mm and transmits data using IEEE802.15.4 compliant radio [10]. Electricity may be also produced by harvesting surplus heat dissipated in HV appliances. Olekshii *et al.* investigated energy recovery from thermal loses generated by HV power transformers by means of thermoelectric modules. Power produced this way was insignificant comparing to the losses and power rating of the transformer and thus it may not be considered a mean to enhance energy efficiency of

power transformers, it may however energize low-power sensors [11]. Drawing power from the heat radiated by the current-carrying busbar is another example of harvesting-oriented approach in HV engineering. Such solution using remote TE-qNODE sensor node supplied by a harvester based on advanced thin-film thermoelectric module has been jointly presented by Micropelt and Schneider companies. Unfortunately, as a commercial construction, it was lacking a comprehensive technical data. The only information made available was the intended application to low- and medium-voltage switchgear, minimal temperature difference between a busbar and surrounding air of 5 K and use of radio link to convey data at 60 s interval between consecutive temperature measurements [12].
The presented paper aimed thus at investigating the feasibility of using a harvester based on regular thermoelectric Peltier module to supply low-power microprocessor-based sensor node to measure temperature of MV armature (like a busbar). The goal of the work was also to explore a practicability of fiber optic link as a mean to transmit measurement data in order to make the harvester-supplied node totally immune to electromagnetic noise and capable of working in enclosed three-phase electric power systems without mutual interferences.

2. Apparatus

A laboratory harvester model was build using a commercially available mid-range thermoelectric module TEC-18351 (I_{max}=3.9 A, U_{max}=15.5 V, P_{max}=34 W, R_{int}=3.5 Ω, 25x25x3.5 mm). The module was fitted with a slotted 9-fin 38x38x20 mm aluminium radiator (thermal resistance unknown), permanently affixed to the module plate with a thermally conductive glue. The radiator-module assembly was placed on a 50 W copper hot plate, simulating a real heat source. The temperature of the hot plate was stabilized using YUDIAN AI-208 PID controller and a Pt100 temperature sensor. Voltage and current output of the thermoelectric module as well as temperature of the heater and the radiator was monitored using a PC-interfaced Agilent 34972/34901A data acquisition unit.

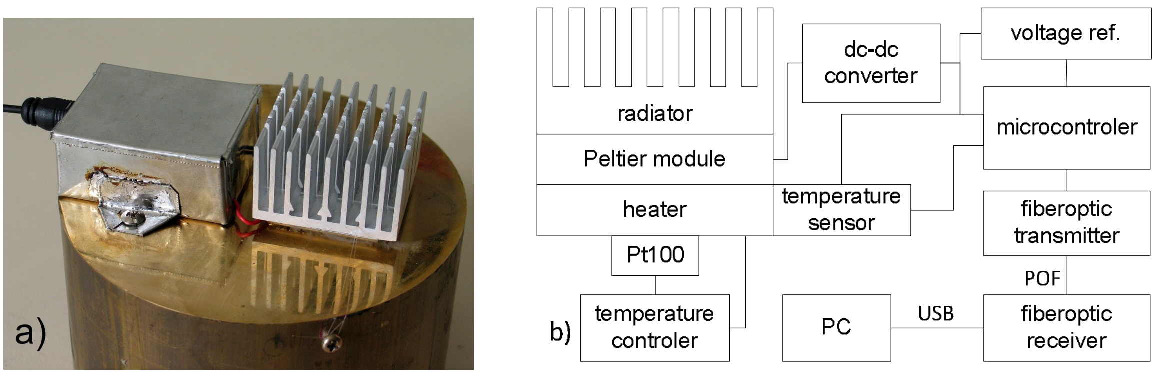

Figure 1. Test set-up: a) thermoelectric harvester and sensor node, b) schematic diagram.

In order to boost a mV voltage output of the thermoelectric module to a level suitable for supplying microelectronic devices an ultralow voltage step-up dc-dc converted was exploited, build using 1:100 step-up transformer (LPR6235-752SML, Coilcraft) and LTC3108 chip (Linear Technology) [13]. Its output voltage was programmed to a minimal permissible value (2.35V). The auxiliary output of the converter (to which sensor node supply terminal was connected) was energized by PGD signal i.e. only when voltage across the main output storage capacitor (470 µF, replaced by 330 µF in the final version of the harvester) was within operational range. Such mode of operation resulted in hysteretic switching the sensor node on for a short interval (when the voltage arrived at 92.5% of the programmed value) and then turning it off (when the voltage dropped below 91 % of the programmed value) for a longer time period until the voltage again reached 92.5% of the programmed value.
A model sensor node was build using ATmega328p (Atmel) microcontroller (µC), clocked at 8 MHz, fitted with MAX6605 precision, low power analog output temperature sensor. Measurement data

IOP Conf. Series: Materials Science and Engineering **113** (2016) 012024 doi:10.1088/1757-899X/113/1/012024

transfer was accomplished using IR LED diode directly driven at 38400 bps by μC USART transmit pin through 330 Ω resistor. The optical power of the LED was channeled to 1 mm in diameter plastic optical fiber (POF) using a modified fixture (FC684208T, Cliff). All PCB-mounted electronic elements were shielded in a small metal enclosure, from which only POF cable and Peltier module electrical connectors were guided, as it was shown in figure 1a.

A fiber optic receiver (custom-build according to a modified Maxim An1117 reference design [14] and using IFD91 PIN photodiode mounted in a modified FC684208T fixture) was used to accept optical signals from the sensor node and translate them into USB datagrams using UART-USB interface chip FT232R (FTDI Ltd.). Measurement data was then recorded using an ordinary PC and a terminal program. A schematic diagram of the entire measurement set-up was shown in Figure 1b.

High voltage laboratory tests, simulating operation in HV conditions were carried out using a large bronze block, heated to 45ºC, on which the harvester and sensor node were mounted (as in Figure 1a). The copper block was HV-biased using HV power amplifier (model 20/20C, Trek Inc.) controlled by a function generator (33522A, Agilent) supplying thus 0-20 kV DC or 50 Hz AC signals.

3. Experimental results and discussion

First of all, open circuit voltage and short current (across 10 Ω current shunt of Agilent 34901A multiplexer) generated by the radiator-thermoelectric module test assembly was evaluated. The assembly was oriented vertically (in order to endorse natural air convection) and placed into a good thermal contact with a test heat source, which temperature was set to 32, 41 and 50 ºC consecutively. All those experiments were carried out in still air at ambient temperature 26 ºC.

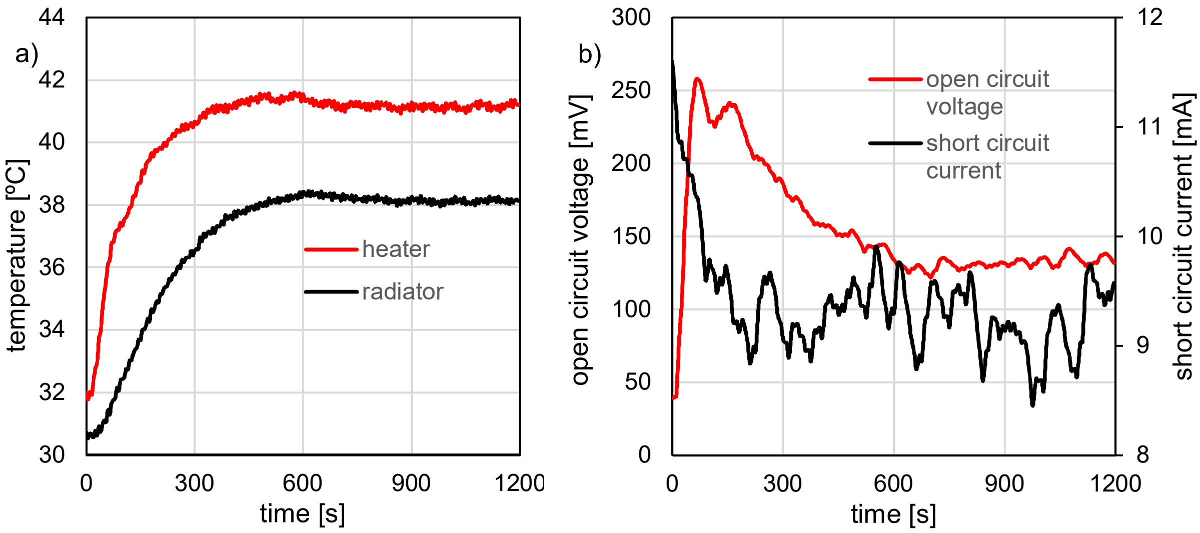

Figure 2. Thermoelectric module test assembly: a) heater and radiator temperature, b) open circuit voltage and current over 10 Ω current shunt.

Exemplary temperature, voltage and current curves recorded for the case of 41 ºC were shown in figure 2 while table 1 lists mean output values obtained in stable thermal conditions. It should be pointed out that in still air at 26 ºC ambient temperature and 32.5 ºC heater temperature (thus at the temperature difference below 7 ºC) approx. 0.15 mW was released at 10 Ω load. Moreover, it should be indicated that 10 Ω test load was not strictly matched with the internal resistance of the thermoelectric module therefore truly available power was slightly underestimated.

IOP Conf. Series: Materials Science and Engineering **113** (2016) 012024 doi:10.1088/1757-899X/113/1/012024

Table 2. Radiator-thermoelectric module test assembly output (mean values in stable thermal conditions, ambient temperature 26ºC, sill air).

heater temperature (ºC)	heater-radiator temperature difference (ºC)	open circuit voltage (mV)	current at 10 Ω load (mA)	power at 10 Ω load (mW)
32	1.4 - 1.6	50 - 55	3.5 – 4	0.1 - 0.2
41	3.0 – 3.2	130 - 140	8.5 – 9.5	0.7 – 0.9
50	4.5 – 5.0	230 - 250	15.5 – 16.5	2.4 – 2.7

Voltage and power output of the thermoelectric assembly was thus far too low to be directly used to supply the sensor node and for its continuous operation. Therefore a boost dc-dc converter capable of operating at mV input voltages was employed together with a capacitive energy storage. The input impedance of the constructed converter was variable, as it may be determined in figure 3a and it was dependent on the input voltage. The impedance changed from approx. 12 Ω at 20 mV to approx. 6.5 Ω at 60 mV, then peaked to approx. 11 Ω at 100 mV and then decreased back to approx. 5.5 Ω at higher voltages, thus it was also not accurately matched with the (catalogue) internal resistance of the thermoelectric module making power transfer from the module to the load not ideal.

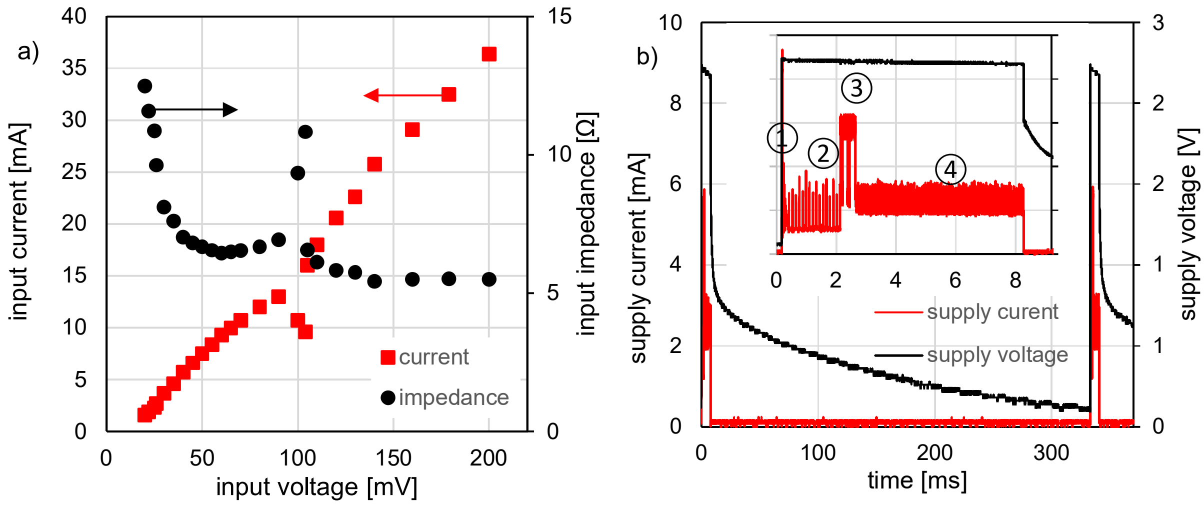

Figure 3. Supply of the sensor node: a) variable input impedance of the dc-dc converter, b) voltage and current trace during 2 on-off cycles.

The sensor node operation was made simple to minimize energy consumption. It was controlled by the firmware code, executed by the µC and the dc-dc converter cyclic operation. After µC power up and initialization (period marked (1) in figure 3b inset) 16 successive 10-bit analogue-to-digital conversions were performed (2) and their 14 bit accumulated result was finally sent out serially using USART and IR LED (3). After that µC operated in an empty loop until accumulated energy was consumed resulting in voltage drop below 91 % of the programmed value and thus sensor node de-energization (4). Such on-off cycle was repeated as soon as the energy transferred from the thermoelectric module to the storage capacitor resulted in voltage rise back to 92.5 % of the programmed value. The supply voltage and current drawn by the sensor node during such recurrent operation was shown in figure 3b. The mean supply current was approx. 2.3 mA while the maximal momentary value (during start-up) was approaching 9 mA; data transfer required approx. 6 mA.

The sensor node was therefore totally dispatched for a period of energy accumulation and resurrected each time enough energy has been collected. The time required by the dc-dc converter to recharge the storage capacitance back to the operational voltage (i.e. the time period between two consecutive run sequences of the µC) was dependent on its input voltage as it was shown in figure 4a. It should be noted that data presented in figure 4a was collected when supplying the node from a laboratory power supply of negligible internal resistance and current capability much higher than the node input current. Input voltage of 26 mV resulted in 0.18 runs/s repetition rate while at voltages exceeding 100 mV more than 5 runs/s were completed. Repetition rate 0.8-1.2 runs/s may be thus expected at 32 ºC when taking into account data in table 1.

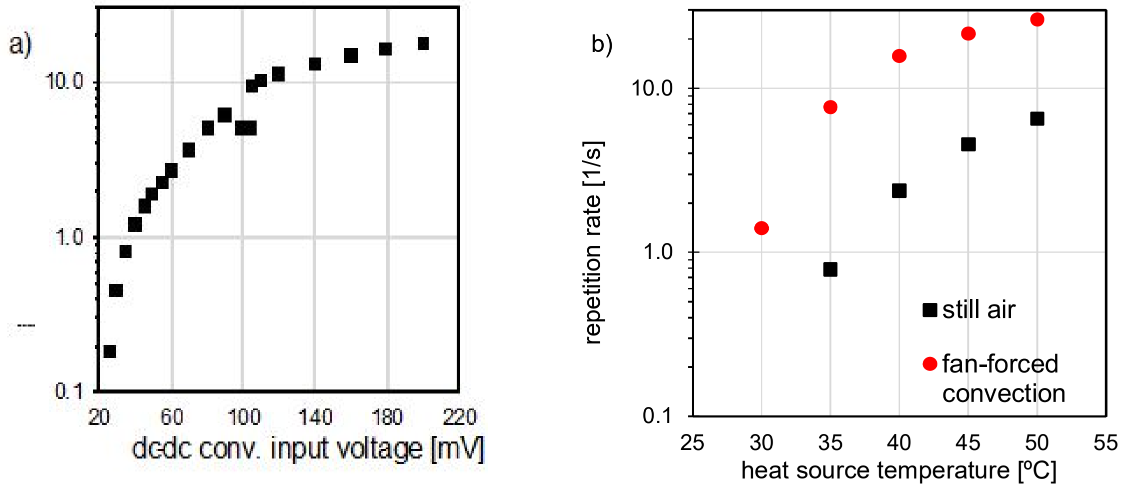

Figure 4. Sensor node on-off repetition rate: a) idealized supply case (laboratory power supply of negligible internal resistance), b) supplied by experimental thermoelectric harvester assembly.

Repetition rate measured when the sensor node was supplied exclusively by the thermoelectric harvester test assembly at 25 ºC ambient air temperature was shown in figure 4b. The minimal heat source temperature necessary to make the sensor node active was 35 ºC in still air (i.e. at 10 ºC temperature difference). The minimal operational temperature was lowered to 30 ºC (i.e. at just 5 ºC temperature difference) when cooling of the radiator was improved by forced air movement, produced by a miniature 0.9 W electric fan positioned 1 m away from the thermoelectric module assembly.

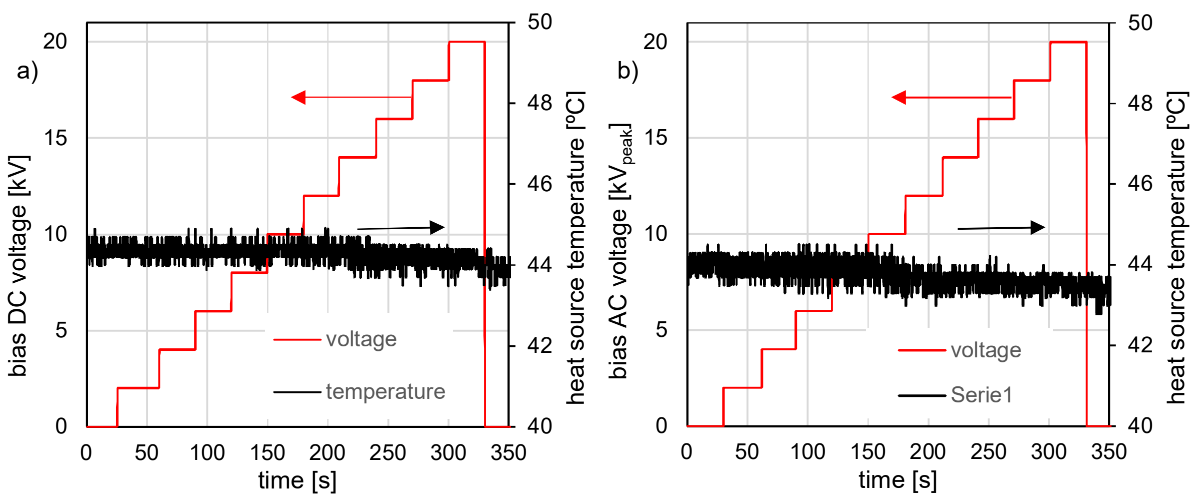

Figure 5. HV-biased sensor node operation: a) 0-20 kV DC, b) 0-20 kV 50 Hz AC.

IOP Conf. Series: Materials Science and Engineering **113** (2016) 012024 doi:10.1088/1757-899X/113/1/012024

Finally the sensor node operation was verified using a HV-biased heat source (heated to 45 ºC and then allowed to naturally cool down). The HV bias was risen from 0 to 20 kV (DC or 50 Hz AC peak value) in 2 kV steps every 30 s and the heat source temperature was monitored by the senor node supplied only from the thermoelectric harvester assembly. Temperature measurement process was not affected by HV step rise as it was evidenced by the temperature records shown in figure 5. The uncertainty type A (expressed at 95 % confidence level) of the temperature measurement performed in the whole bias voltage range 0-20 kV was not worse than 0.9 ºC; it was to some extent higher for HV AC bias (0.9 ºC) than for DC (0.7 ºC) but such difference may be considered insignificant.

4. Conclusion

It was shown that a commercial mid-sized thermoelectric Peltier module passively cooled with a small radiator was capable of generating electrical energy which boosted in voltage and capacitively accumulated may be used to power up low-power microcontroller-based sensor node at sub-second intervals. Model sensor node fitted with such energy harvesting assembly was operative at temperature difference between the heat source and ambient, still air of at least 10 ºC while just 5 ºC was sufficient in augmented cooling conditions. Infrared fiber optic data transfer was also a technically feasible solution in case of such low-power supply approach making the sensor node unaffected by electromagnetic interferences. Properly shielded and thermoelectrically-supplied sensor node may be safely operated under biased conditions up to 20 kV DC and 50 Hz AC making such solution useful in remote monitoring of armature in MV switchgear.

5. References

[1] Matiko J W, Grabham N J, Beeby S P and M J Tudor 2014 Review of the application of energy harvesting in buildings *Meas. Sci. Technol.* **25** 012002

[2] Harne R L and Wang K W 2013 A review of the recent research on vibration energy harvesting via bistable systems *Smart Mater. Struct.* **22** 023001

[3] Davidson J and Mo Ch 2014 Recent advances in energy harvesting technologies for structural health monitoring applications *Smart Mater. Res.* 2014 ID 410316

[4] ed Elvin N and Erturk A 2013 *Advances in energy harvesting methods* (New York: Springer Science + Business Media)

[5] ed Tan Y K 2013 *Energy harvesting autonomous sensor systems: design, analysis, and practical implementation* (Boca Raton: CRC Press Taylor & Francis Group)

[6] Zangl H, Bretterklieber T and Brasseur G 2009 A feasibility study on autonomous online condition monitoring of high-voltage overhead power lines *IEEE Trans. Instrum. Meas.* **58** 1789–96

[7] Guo F, Hayat H and Wang J 2011 Energy harvesting devices for high voltage transmission line monitoring *Proc. IEEE 2011 Power and Energy Society General Meeting* 24-29 July 2011, San Diego, CA USA

[8] Zhu M, Judd M D and Moore P J 2009 Energy harvesting in substations for powering autonomous sensors *Proc. SENSORCOMM 3rd Int. Conf. Sensor Tech. and App.* Athens Glyfada 2009, 246–51

[9] Roscoe N M and Judd M D 2013 Harvesting energy from magnetic fields to power condition monitoring sensors *IEEE Sens. J.* **13** 2263–70

[10] http://micropelt.com/mnode.php, hyperlink valid on 17.10.2015

[11] Olekshii R, Kukla N and Linkevics O 2014 Feasibility of usage of thermoelectric modules for recovering of low-potential heat from a surface of power transformers *RTUCON 55th Intl. Scientific Conf. on Power and Electrical Engineering,* Riga Technical University 124–9

[12] http://www.micropelt.com/applications/te_qnode.php, hyperlink valid on 17.10.2015

[13] LTC3108 Ultralow voltage step-up converter and power manager Linear Technology Corporation datasheet LT 0813 rev. C
[14] Small photodiode receiver handles fiber-optic data rates to 800kbps 2001 Maxim Integrated Products Application Note 1117