A Diverse Monitoring for Post-Accident using Alternative Powers

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Abstract
After the Fukushima accident, nuclear industry has launched quite exhaustive research projects to address safety challenges in Beyond Design Basis Accident (BDBA). It has been suggested that the Severe Accident Management Guidelines (SAMG) could only be useful if the monitoring of critical parameters is somehow made available to the operator, even in SBO condition. A task of this research is to develop self-powered sensors that can function under a loss of power event, and to incorporate them with plant communication for data transmission and remote actuation. Design of a sensor network to optimize fault monitoring is part of the research effort with applications to a typical PWR. This research will focus on developing self-powered sensors, a sensor network strategy, and data communication and control.

Keywords: Energy Harvesting, Self-powered, Condition Monitoring, Remote Sensing

1. INTRODUCTION
The March 2011 accident at the Fukushima Dai-ichi nuclear power station emphasized the importance of analyzing events that are beyond design-basis conditions, and their mitigation. This safety issue is highlighted in the July 2011 US NRC report titled, “Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident”\textsuperscript{[1]}. The report emphasized the need for monitoring core and coolant system conditions, sustainability of sensor measurements of critical safety functions during prolonged SBO and depleted electric power, and the ability to communicate sensor measurements and other information during a severe accident condition \textsuperscript{[2]}. Energy harvesting is the process of collecting the ambient energy from the surroundings like light, heat, vibration, and electromagnetic radiation, and converting it into usable electrical energy for power portable electrical devices; this can be done without using the batteries. This technology efficiently collects the ambient energy that we usually discard and merits a lot of attention. It is also known as energy scavenging or power scavenging\textsuperscript{[3]}.

2. SELF-POWERED ENERGY HARVESTING INSTRUMENTS FOR MONITORING CRITICAL SAFETY FUNCTION DURING AN SBO
The station blackout (SBO) makes it difficult to monitor critical parameters (e.g. reactor water level, pressure, temperature, etc.) and open critical safety valves (e.g. safety/relief valves, isolation condenser return valves, containment vent valves), which in turn lead to fuel and containment overheating and damage. Self-powered (charged) low-power sensors for remote sensing, together the passive and active electric power supply systems are desirable to
overcome the station blackout scenario[4]. These sensors are self-charged low power equipment or have self-powered batteries that charge themselves using vibration energy, deviation of temperature or pressure, and solar energy[5]. Figure 1 shows an outline of the self-powered (charged) instruments as alternative power sources using energy harvesting technologies for monitoring critical safety function during an SBO.

3. DEVELOPMENT OF THERMOELECTRIC EH PROCESS SENSORS

3.1 Thermoelectric Energy Harvesting Devices
Thermoelectric Devices have been composed in order to examine that the electrical power generated from a thermo-electrical generator is possible to operate a wireless sensor. The functionality of the sensor is verified by the process value received and displayed on a computer in the remote distance[6][7]. The thermoelectric device obtains heat energy from a hot surface in a plant and convert it a small electrical energy for the sensor. Radiation fins are welded to the cold surface for cooling purpose. The thermoelectric EH(energy harvesting) device has the size of 40 x 45 mm with 4mm in depth as shown in figure 2.

Figure 1. An outline of the self-powered (charged) system for instruments for monitoring critical safety function during an SBO

Figure 2. A thermo-electrical module for self-powered wireless sensor application
3.2 Electrical Output Performance Testing

Before installation in a thermo-hydraulic testing facility, the performance of the assembled thermoelectric EH device is tested. Figure 3 shows a view of the testing setup in which the harvested electrical energy is measured.

![Figure 3. Performance testing of the assembled thermo-electrical module for self-powered wireless sensor application](image)

The thermo-electrical module has generated approximately 1W at $75\, ^\circ\text{C}$ temperature difference. Table 1 illustrates the output values of the generator in accordance with change of temperature. The electricity of 1 W is the amount of energy which can afford to run two pressure sensors transmitting a 4-20mA analog output signal.

<table>
<thead>
<tr>
<th>ΔT ($^\circ\text{C}$)</th>
<th>No Load</th>
<th>Load (5Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V)</td>
<td>0.32</td>
<td>0.23</td>
</tr>
<tr>
<td>Current (A)</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>1</td>
<td>0.69</td>
</tr>
<tr>
<td>Current (A)</td>
<td>0.32</td>
<td>0.27</td>
</tr>
<tr>
<td>Power (mW, $P=V \times I$)</td>
<td>20.7</td>
<td>0.47</td>
</tr>
</tbody>
</table>

3.3 Application experiment of thermoelectric energy harvesting device

3.3.1 Site Survey and Installation

A site survey for seeking an appropriate hot surface location to attach the assembled thermoelectric device has been conducted in a testing facility in KAERI which is built for simulating various thermodynamic behaviors of the primary coolant system of a small modular nuclear power plant. Figure 4 contains two examples of the images obtained from the facility during the site survey. Figure 5 shows the real view of the thermoelectric EH
device installed at the holder of the main coolant pipe. The output electricity is connected to a wireless sensor module to verify that it is functioning properly as designed.

Figure 4. Examples of infrared images on the surface of the main coolant pipe in the KAERI testing facility

Figure 5. A thermoelectric energy harvesting module attached in the holder of a main coolant pipe.

4. DEVELOPMENT OF VIBRATION EH DEVICES

4.1 Design of Electromagnetic self-powered device

The electromagnetic energy generating device is the resonance self-powered device and is designed to the size 60 mm x 60 mm x 70 mm (width x depth x height) and the resonance point among 26 – 29 Hz. The specific range has been derived from the resonance frequency of the target application, i.e., a coolant inlet line, located on the 3rd floor of SMART-ITL (complex testing facility for thermo-hydraulic testing purposes) at KAERI. Figure 6 shows the fabricated resonance self-powered device.

Figure 6. Diagram of actual fabricated device, device model, and the device model with a fixture
Figure 7 shows the actual vibration frequencies and amplitudes measured from three locations around the testing facility. In this figure, the location that shows the highest amplitude is the vertical direction of a coolant inlet line, thus considering this requirement; we have designed and fabricated a self-powered module for vibration type including a dedicated fixture fitted with the resultant resonant frequencies on the testing place of the site. In the practical application, since the intrinsic frequencies are slightly changing with the operating conditions, the testing performance shows different resultant frequencies away from the resonance frequencies. This is because the operating mode would be changing with the operating conditions of the testing device.

4.2 Design of Piezoelectric self-powered device

The fabricated piezoelectric generating device has the function of controlling the resonance frequencies by attaching a scale weight to a cantilever beam. We have summarized the results of measuring the vibration on the 2nd floor of the operating testing facility as shown figure 8. From the results, the piezoelectric energy element has been designed and fabricated in such a way that its size is 100 mm x 100 mm (width x depth) and its resonance point is one of 20, 30, 60, and 120 Hz. Figure 9 shows the fabricated piezoelectric generating device.

This fabricated piezoelectric self-powered device consists of a piezoelectric module generating the power from vibration and a capacitor which stores the DC (direct current)
power that is transformed by full-wave rectification from the AC (alternating current) generating power. To develop the device, a performance evaluation system has been configured, as shown in figure 10. The resonance frequency of the developed piezoelectric self-powered device has been adjusted to the resonance point.

Figure 9. Diagram of the fabricated piezoelectric self-powered device

Figure 10. Structure of the performance evaluation system for a piezoelectric self-powered device

4.3 Performance testing of the vibration self-powered module

In order to demonstrate the site applicability on the developed device, we have tested the device to apply to SMART-ITL at KAERI. The electromagnetic self-powered device was installed on the 3rd floor and the piezoelectric self-powered device was installed on the 2nd floor. Figure 11 shows the self-powered wireless transmitter attached to a pipeline and the receiving results from the data storage/display device. The current self-powered device functions in such a way that if the amount of power charge is reached to the sufficient level to operate the whole device fully, then the overall device could be restarted and send the current parameter values of both the temperature and the pressure. As in the current design, the power source from vibration has still some limitation for the whole device to continuously operate. Thus, the operating time of the device should be changed according to the total storage amount of the power charged. When the power storage harvesting from vibration is charged with some predetermined amount through the sufficient voltage, then the wireless sensor module could be started to operation and transmit the current values of the parameters, then hibernates in a stand-by mode. If the amplitude of vibration is high, then the interval of data transmission time would be shortened, whereas if the amplitude of vibration is low or the resonance point is unmatched, the interval time would
be lengthened. Table 2 shows a result of voltage output via vibration frequency of performance testing for a vibration based self-powered module. Figure 12 shows a peak electric power via vibration frequency of performance testing for a vibration based self-powered module.

Table 2. Result of voltage output via vibration frequency of a vibration based self-powered module.

<table>
<thead>
<tr>
<th>Condition of Test</th>
<th>Output Voltage</th>
<th>Result of Testing</th>
</tr>
</thead>
</table>
| 26Hz 0.21g        | ![Graph](image1.png) | Output Voltage : 1.86Vrms  
Internal resistance : 360Ω  
Estimation power : 19mW  
mass : 394gram |
| 29Hz 0.18g        | ![Graph](image2.png) | Output Voltage : 1.32Vrms  
Internal resistance : 360Ω  
Estimation power : 9.6mW  
mass : 252gram |

Figure 11. Self-powered remote transmitter and the display results of the receiving data

Figure 12. A peak electric power via vibration frequency of a vibration based self-powered module.
5. DEMONSTRATION OF WIRELESS SENSOR NETWORK USING SELF-POWERED EH DEVICES

5.1 Configuration for demonstration of the self-powered EH devices

The self-powered EH module consists of the thermoelectric EH device, the electromagnetic type device and the piezoelectric self-powered device for demonstration of performance of EH devices. We have tested a low-powered wireless sensor network using these electric power generating modules. Figure 13 shows a schematic diagram of the wireless sensor network for demonstration of self-powered EH device which can use the electric power generated from the vibration on the testing facility, monitor the parameters of the atmospheric pressure and the ambient temperature, and send those values to a receiver module. The operating power related to the data sending part is provided by the power generation from vibration, and the power of the receiver module is provided by using the peripheral power source of electrical line. The temperature sensor device is driven by using a power transformer, which is provided by both the electromagnetic and the piezoelectric type energy generating modules, and a power management device which can manage the generated power. Then, the parameter value of the temperature can be sent to the receiver via a wireless device.

Due to the magnitude of the self-powered is very low level, the power management device that can efficiently manage the overall amount of the generated power should be required. Namely, when the generating power is insufficient or nothing to generate, the operation of the temperature device and wireless device, i.e., electrical loads, would be turned off, whereas when the generating power is guaranteed to be sufficiently generated, then the devices can be restarted and can send the parameter values of both the temperature and the pressure. The data storage/display device can store the transmitted data and display these data to a user. This device is a PC-based system that uses a Labview-based data processing program.

Figure 13. Schematic diagram of wireless sensor network for demonstration of self-powered EH device
5.2 Application to Wireless Sensor Operation of the Self-powered EH Devices

The unsteady electrical voltage converted from the heat or vibration by thermoelectric and/or electromagnetic energy harvesting devices is supplied to a power management circuit for voltage regulation. This circuit makes the fluctuating high input voltage to a steady output voltage necessary to operate a wireless sensor. Also, it turns off the transmitting module when the input voltage is too small to transmit a signal to the receiver and turns on the module when the voltage is recovered. Figure 14 shows some real views of installation of a wireless sensor system in which the electric power is supplied by the energy harvesting devices from the main flow pipe.

![Figure 14. Energy harvesting device and wireless sensing system installed at the site](image)

5.3 Application Results

The testing result of functionality of the wireless sensing module whose power is supplied by the energy harvesting devices is illustrated in figure 15. It demonstrates that the energy harvesting module generates electrical power enough to drive the wireless sensing system which is measuring temperature and pressure. Therefore, it can be concluded that even the current energy harvesting technologies are feasible to be used as an emergency power supply as far as the proper locations of hot surface or vibration equipment exist in a plant.

![Figure 15. Testing Result of wireless sensing system powered by an energy harvesting module](image)
6. CONCLUDING REMARKS

Although the self-powered device using the vibration can generate some degree of power at the laboratory scale, if the device would be incorporated to the real testing facility, the amount of power generation would be a little due to slightly variations of the resonance frequency. Thus, in order to apply to real applications, the difficulties in detecting the appropriate resonance frequency on the fixture place should be resolved in the near future through the long-time operating experiences using the device. Although the current self-powered development seems to be at the R&D stage, if the device or composition material with more broadened band of resonance frequency will be developed, it is expected that this device will be applicable to the severe conditions of an emergency operation such as a loss of power. If the self-powered module having several resonance frequencies will be developed, the necessity of the self-powered device will be more closely approaching to the practical use. But, in this case, the disadvantages of high manufacturing cost and large size of the device will be expected. The device employing a wireless sensor network using vibration might be a possible candidate for detecting the effective data such as the sensors of temperature, flow rate and pressure, especially installed at the inaccessible locations. However, much more R&Ds should be required to apply to the real on-site applications. Also, the practical use will be expected in more soon if electronic devices operating with lower power would be developed.

REFERENCES