Introduction of Products

Thermoelectric Energy Harvesting Vibration Monitoring Device KSGD-SV

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According to a survey in 2018 conducted by the Japan Machinery Federation, 50% to 80% of machine tools, secondary operation machine, and foundry equipment have been installed for 15 years or more. Retirement of veteran employees in charge of equipment maintenance is in progress. Predictive maintenance (PdM) is becoming more important by detecting signs with monitoring equipment and perform maintenance at the right time. Although the cost reduction of sensors is progressing, the introduction of PdM is limited to some equipment with large opportunity loss from downtime due to the problems of installation and operational costs of monitoring devices. Much equipment continues to undergo patrol inspections.

KELK Ltd. has developed the battery-less and wiring-less monitoring device "thermoelectric EH (Energy Harvesting) vibration monitoring device KSGD-SV." This paper describes the features and usage of KSGD-SV that detects signs of failure of rotating equipment, which has the highest ratio of equipment failure causes in the KELGEN SD product group.

Key Words: *Thermoelectric generation, Energy harvesting (EH), Predictive Maintenance (PdM), Vibration sensor*

1. Introduction

KELK was established in 1966 as a manufacturer of applied products of thermoelectric (T/E) elements, with the predecessor of the T/E semi-conductor research and development department, which Komatsu launched in 1957. The company consistently develops, manufactures, and sells materials, modules, heat exchangers, and applied equipment for thermo-modules (T/E element modules) that use T/E semi-conductors for temperature control, and is leading the market as the world's top manufacturer in the business of temperature controlling equipment for semi-conductor manufacturing machines. It is also a leading company in T/E generation which converts heat into electricity by using T/E semi-conductors, developing the element technologies to the applied products. It provides T/E generation products with outputs ranging from button-battery-level mW to industry-level kW and their application products.

2. Mechanism of thermoelectric generation

T/E generation is a technology that applies the Seebeck effect (**Fig. 1**), which directly converts heat into electricity through a material called a T/E semi-conductor. The Seebeck effect is a phenomenon that when a temperature difference occurs between the ends of a metal or a semi-conductor, a difference in the concentration distribution of electrons or holes is caused to generate an electromotive force (thermal electromotive force).

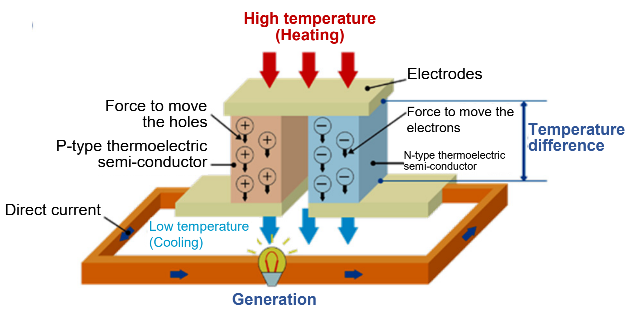

Fig. 1 Principle of the Seebeck effect

The T/E generation module consists of a number of P- and N-type T/E semi-conductor elements that are alternatively series-connected with metal electrodes as in **Fig. 2**. This structure causes the thermal electromotive force of each T/E semi-conductor element to be accumulated in the same heat flow direction, resulting in the generation of larger voltage. As its power supply, the KELGEN SD uses the electric power self-generated by the temperature difference arising across the mounted T/E power generation module KELGEN.

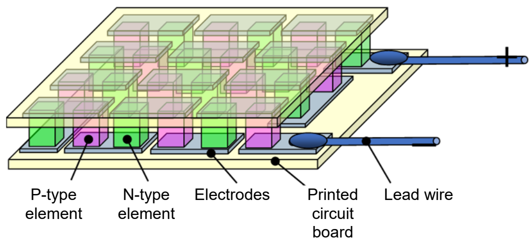

Fig. 2 Standard structure of T/E module KELGEN

3. KELGEN SD power generation unit

T/E semi-conductor elements have weaker mechanical strength than other metal materials. In addition, when they come into contact with moisture, they break due to migration or short circuits. Meanwhile, if a T/E semi-conductor element is protected by directly covering it with a resin or the like, the temperature difference between its ends decreases, resulting in a significant decrease in power generation efficiency. KELK has developed a dustproof and waterproof power generation unit (PGU; **Fig. 3**), which reduces the effects of mechanical impact and thermal deformation on KELGEN, maintains the temperature difference between the T/E semi-conductor element ends and complies with the protection class IP67 standard.

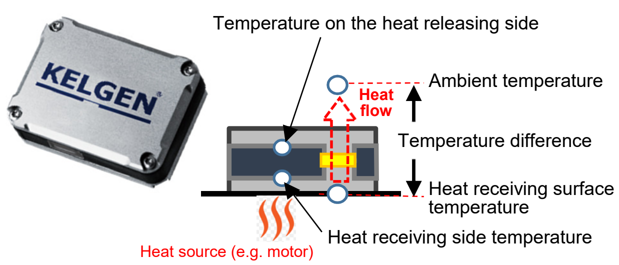

Fig. 3 Appearance and temperature measuring points of the KELGEN SD PGU

4. Motor waste heat and KELGEN SD power generation performance

Although energy conservation has been evolving in motors, 5% to 15% of the electric energy input is discarded as heat energy depending on its efficiency (**Fig. 4**).

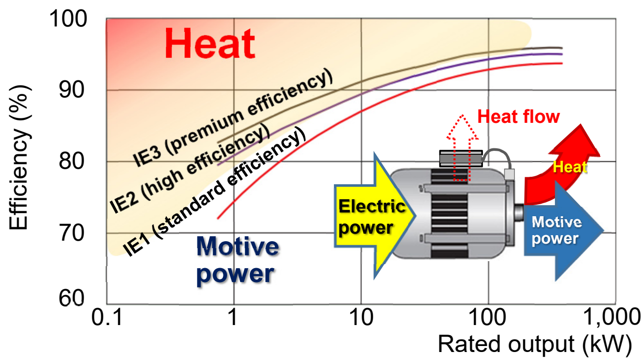

Fig. 4 Comparison of motor efficiency values (IP4X, 50 Hz, 4-pole, 200 V) [1]

Just by being placed on the operating motor, the KELGEN SD begins to generate electricity when the temperature difference between the motor surface and atmosphere reaches 10°C or more.

The temperature of the entire KELGEN SD changes depending on the amount of heat received from the surrounding environment (excluding waste heat from motors, etc.), which changes depending on the day/night, the weather, and the season. Meanwhile, when the motor operates, the electric energy is partially converted to waste heat depending on its efficiency, causing the motor surface temperature to be higher than that of the surrounding environment. When the motor operates, the KELGEN SD installed on the motor surface generates electricity by the temperature difference between the heat receiving and radiating surfaces.

We installed the PGU of KELGEN SD on an exhaust motor placed under a constant outdoor load and evaluated the power generation performance responding to day/night and weather changes (**Fig. 5**). On June 19 (fine), the motor surface temperature changed by 15°C between day and night, but the temperature difference between the installation and radiating sides of the PGU was constant. On June 20 (rainy), the PGU was temporarily cooled by nearly 10°C due to rainfall from 7:00 to 12:00, but the temperature difference of the PGU that receives a constant-temperature waste heat from the motor was almost constant. In addition, we evaluated the temperature difference between the installation and radiating sides of the PGU responding to the temperature change between August and December; as a result, we verified that the temperature difference in the PGU was constant although the ambient temperature difference was 30°C or more.

The PGU of KELGEN SD can maintain a stable temperature difference responding to changes in day/night, weather, and seasons and generates stable electric power.

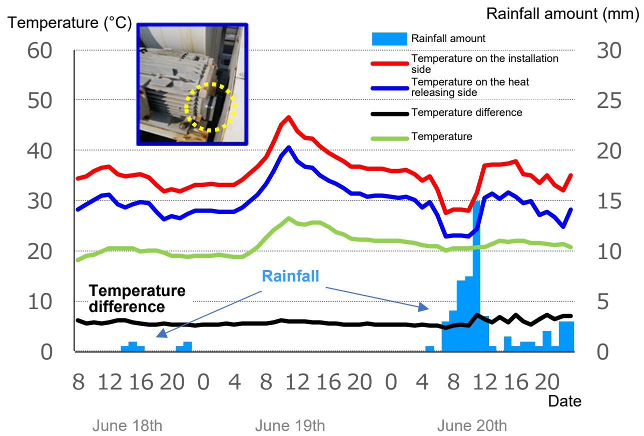

Fig. 5 Temperature difference between the heat receiving and radiating surfaces of the KELGEN SD PGU installed on the outdoor exhaust motor

5. Equipment failure and PdM

According to a report [2] of the US Department of Energy, PdM, which detects failure signs and performs maintenance before failure at the right time, can reduce maintenance costs by 10% compared to preventive maintenance and also has the effect of reducing downtime. Meanwhile, installing a failure sign detection system requires capital investment and investment in maintenance personnel education.

Half of the equipment failures occurred in rotating equipment including rolling bearings, hydraulic pumps, gears, and plain bearings. [3]

When rotating equipment caused an abnormality, it exhibits an abnormal vibration in the initial stage and then generates an abnormal noise and abnormal temperature before reaching the failure (**Fig. 6**).

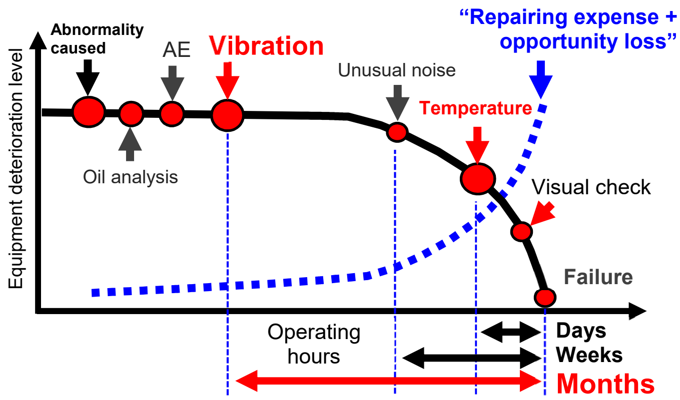

Fig. 6 Concept of signs and losses by failure [4]

Vibration abnormalities have a longer period from the time of occurrence to failure than that for temperature abnormalities. Thus, we can procure maintenance parts at the right time and perform planned maintenance before failure and can prevent opportunity loss caused by downtime and reduce maintenance costs. Monitoring by vibration is demanded for the purpose of failure sign detection of rotating equipment, but the installation cost is an issue for a wired vibration sensor, and operational cost by battery replacement is an issue for a battery-powered vibration sensor; the introduction of the monitoring with vibration sensors is not progressing.

6. Thermoelectric EH vibration monitoring device KSGD-SV

KELK has developed a practical level failure sign detection vibration sensor, the "T/E EH Vibration Monitoring Device KSGD-SV," which operates by self-power generation by T/E EH by improving T/E conversion efficiency and reducing power consumption. Since the KSGD-SV can be installed without wiring and it operates continuously without batteries, the installation and operational costs of the vibration monitoring device can be significantly reduced.

A general vibration monitoring device sends the measured waveform data to the analyzer. The analyzer analyzes the received waveform data and monitors the results of the analyzer. KELK has performed a prototype development of a vibration monitoring device with this configuration and evaluated it. The prototype measures 255 points of vibration waveforms on each of the three axes and sends the waveform data to the analyzer via Bluetooth. For one vibration measurement using the prototype, it was necessary to store electricity for 10 hours in an installation environment with a temperature difference of 25°C. Therefore, KELK improved the T/E conversion efficiency and reduced power consumption in order to bring the vibration monitoring device by T/E EH to a practical level.

(1) KSGD-SV standard configuration

The KSGD-SV, which has a KELGEN T/E generation module, consists of a PGU and a sensor unit having a vibration sensor (**Fig. 7**); the PGU begins to operate at a temperature difference of 10°C by T/E EH. The measurement results were sent wirelessly.

Fig. 7 Appearance of T/E EH Vibration Monitoring Device KSGD-SV

(2) Improving the T/E conversion efficiency

To increase the T/E conversion efficiency (η) of **Formula 1**, we need to increase the performance index Z or temperature difference ΔT_j of the T/E power generation element.

The KELGEN SD uses a KELGEN T/E power generation module with T/E material having a large value of performance index *Z*. To increase ΔT_j, we have developed a PGU with a structure that efficiently transfers the received heat to the heat receiving surface of KELGEN and stably transfers the heat to the outside air from the heat radiating surface.

$$\eta = \frac{P_g}{Q_a} = \frac{\Delta T_j}{T_{hj}} \cdot \frac{\frac{m}{1+m}}{1 + \frac{1+m}{Z T_{hj}} - \frac{\Delta T_j}{2T_{hj}(1+m)}}$$

To increase the T/E conversion efficiency

Increase the temperature difference ΔT_j.

Increase the performance index *Z*.

η : T/E conversion efficiency
P_g : Power generated by T/E conversion element
Q_a : Heat input
ΔT_j : Temperature difference between the T/E element ends
T_{hj} : Temperature at the T/E element heat receiving end
m : (External load resistance)/(Internal resistance of element)

Formula 1 T/E conversion efficiency (η)

(3) Reducing the power consumption

We reviewed the vibration sensor function and reduced the power consumption of the monitoring device, for example, by shortening the data transmission time and eliminating the maintenance of the communication standby state of the monitoring device.

The time of data transmission from the vibration sensor was reduced by changing the method so that the waveform data is calculated in the KELGEN SD and only the result is sent.

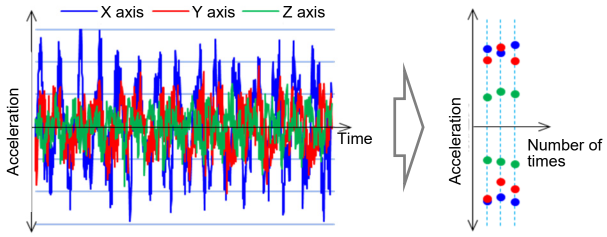

Fig. 8 Change from waveform data to the transmission of calculation results

IoT terminals, which use two-way communication such as Bluetooth, ISA100, or WirelessHART as the communication system, have to maintain the state of waiting for reception. Since the standby state cannot be maintained with a small amount of power generated by EH, KELK has developed KELGEN SD-Net, a communication network for the KELGEN SD, which does not require the maintenance of the standby state.

By improving the T/E conversion efficiency and reducing power consumption, we have developed the practical level T/E EH vibration monitoring device KSGD-SV2, which achieves the number of measurement points four times that of the prototype and an electricity storage time of 30 minutes (1/20) even at a temperature difference of 10°C.

Table 1 Prototype and KSGD-SV2 measurement specifications

Name	Frequency range (±3 dB)	Measurement points	Sampling frequency	Data transmission			Axis	Temperature difference and measurement interval	
				Item	Points	Communication standard		10°C	25°C
Prototype	-	255	1.0 kHz	Acceleration waveform	255 × 3	Bluetooth	XYZ	-	10 hours
KSGD-SV2	2.6 kHz	1,024	6.7 kHz	Travel speed RMS	1	IEEE 802.15.4	XYZ	30 minutes	-
				Acceleration PEAK, RMS, CF, and OA value	3 each				
					3 each				

Table 2 KSGD-SV2 standard specifications

<table>
<tr><th colspan="3">Item</th><th>Standard specifications</th></tr>
<tr><td rowspan="4">Head</td><td rowspan="2">Vibratory acceleration sensor</td><td>Measuring range</td><td>±16G</td></tr>
<tr><td>Sampling frequency</td><td>6.7 kHz</td></tr>
<tr><td rowspan="2">Temperature sensors</td><td>Measuring range</td><td>-20°C to 80°C</td></tr>
<tr><td>Measurement error</td><td>Within ±5°C</td></tr>
<tr><td rowspan="2">Power supply part</td><td rowspan="2">Temperature sensors on the top and bottom face</td><td>Measuring range</td><td>10°C to 85°C</td></tr>
<tr><td>Measurement error</td><td>Within ±5°C</td></tr>
<tr><td rowspan="2">Power supply</td><td colspan="2">Power supply method</td><td>Self-generation with temperature difference.
No batteries installed.</td></tr>
<tr><td colspan="2">Power supply characteristics</td><td>Operated at a minimum temperature difference of 10°C (no wind) or more</td></tr>
<tr><td rowspan="3">Radio</td><td colspan="2">Communication system</td><td>Compliant with 2.4 GHz IEEE 802.15.4</td></tr>
<tr><td colspan="2">Communication channel</td><td>25 ch (2.474 - 2.476 GHz)</td></tr>
<tr><td colspan="2">Encryption</td><td>Compliant with AES 128-bit encryption</td></tr>
<tr><td colspan="3">Protective characteristics</td><td>IP67</td></tr>
</table>

(4) Installation

For installing the PGU of KSGD-SV, we should select a place where the surface temperature is at least 10°C higher than the atmosphere. However, the surface of the place with a temperature difference generated is not always flat. Therefore, KELK recommends the use of resin putty or metal putty to efficiently transfer heat to the PGU of KELGEN SD even on uneven surfaces. Heat can be efficiently received from rotating equipment and others by filling the gap between their surfaces and the KSGD-SV PGU with putty.

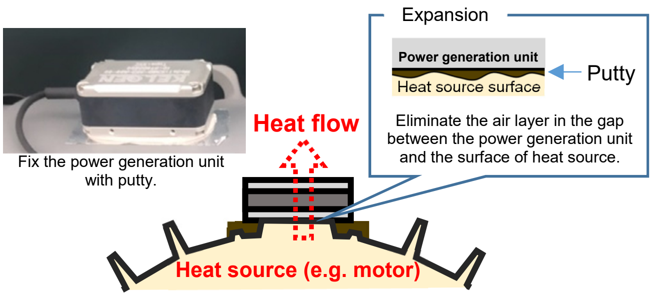

Fig. 9 How to install the PGU

Table 3 Thermal conductivity of sealing compounds

Item	Resin putty	Metal putty	Air (reference)
Heat transfer (W/mK)	Small 0.2 to 1.5	Large 1.0 to 10	Very small 0.025
Adhesiveness	Smaller than metal putty	High	-
Cost	Low	High	-

7. KSGD-SV2 performance and comments

KELK measured each vibration using the KSGD-SV2 as follows and evaluated the abnormality detection performance (**Table 4**): changing the bearing scratched and imbalanced conditions after preparing a bearing with dents attached to the periphery and a flywheel with a 0.7 g hexagon socket set screw attachable to the motor shaft (**Fig. 10**).

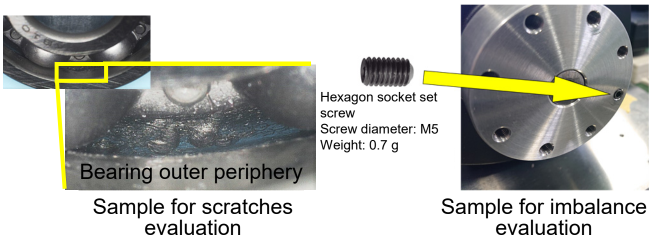

Fig. 10 Sample for vibration evaluation

Table 4 Measured values

Measurement item		Unscratched		**Scratched**	
		Balance	**Imbalance**	Balance	**Imbalance**
Vibratory acceleration (relative)	PEAK	1.0	1.0	**2.3**	**2.3**
	RMS	1.0	0.7	**3.3**	**3.2**
	OA	1.0	0.5	**11.0**	**10.4**
	CF	1.0	1.4	0.7	0.7
Travel speed RMS [mm/s]		1.6	**2.8**	1.2	**2.4**
Vibration sensor unit temperature		36°C	36°C	38°C	38°C

The standard value used was the vibration value of the motor in a balanced state with no scratches on the bearing. The measurement results showed that for motors with scratched bearings, the acceleration PEAK and acceleration RMS exceeded the doubled value and the acceleration OA value exceeded 10 times. In addition, the travel speed RMS value increased in the imbalanced state. The above measurement results demonstrated that the KSGD-SV2 is effective as a vibration sensor for detecting failure signs of the motor.

The KSGD-SV2, which launched into market in February 2020, received the "TPM Excellent Product Award (Development Award) 2020" from the Japan Institute of Plant Maintenance and received "'CHO' MONODZUKURI Innovative Parts and Components Award 2020 (Electrical and Electronic Components Award)" from MONODZUKURI. Nihon. Conference and THE NIKKAN KOGYO SHIMBUN, LTD.

8. KSGD-SV4

KELK further improved the power generation conversion efficiency and reduced power consumption, and, in January 2021, developed KSGD-SV4, which has a significantly increased frequency range and sampling points compared to the KSGD-SV2 and has improved measurement performance.

Table 5 Comparison of measurement specifications between KSGD-SV2 and -SV4

Name	Frequency range (±3 dB)	Measurement points	Sampling frequency	Data transmission			Axis	Temperature difference and measurement interval	
				Item	Points	Communication standard		10°C	15°C
KSGD-SV2	2.6 kHz	1,024	6.7 kHz	Travel speed RMS	1	IEEE 802.15.4	X Y Z	30 minutes	12 minutes
				Acceleration PEAK, RMS, CF, and OA value	3 each				
					3 each				
KSGD-SV4	7.5 kHz	7,168	26.7 kHz	Travel speed RMS	1	IEEE 802.15.4	Z	40 minutes	16 minutes
				Acceleration PEAK, RMS, CF, and OA value	1				
					1				
				Envelope FFT	5				

The KSGD-SV4, which has a frequency range of 7.5 kHz (±3 dB) and vibration measurement performance for 7,168 measurement points, can sense initial abnormalities in bearings. In addition, the KSGD-SV4 is the first T/E EH vibration monitoring device provided with the envelope FFT analysis function (**Fig. 11**), which is provided in wired and portable vibration diagnostic meters. The envelope FFT analysis function, which analyzes the periodic shock wave period generated when rotating equipment is abnormal, assists in identifying the location of its failure. The portable KSGD-SV4, which has improved performance to the vibration sensor level, assists in the abolition of patrol inspections by maintenance personnel.

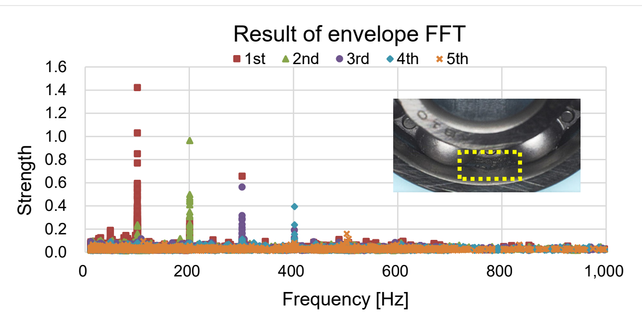

Fig. 11 Envelope FFT result of bearing outer ring scratches

9. KELGEN SD-Net (KSGD-SV communication network)

The KELGEN SD communication network, KELGEN SD-Net, may be either of two types: a standard network that can connect about 200 units and a small network that can connect about 30 units. The standard network allows us to configure up to 3 communication paths, improving its redundancy and robustness. The receiver aggregates the KELGEN SD data and sends it via Ethernet. The output data from the receiver can be received by a data management PC or by a sequencer or the like by customizing the output data. The small network uses repeaters to send KELGEN SD measured data to the receiver through up to 5 hopping stages. The receiver outputs the received data by serial communication.

Since the radio wave condition changes depending on the installation location and surrounding environment of the monitoring device, the communication network repeaters should be deployed according to the surrounding environment. KELK prepared software that visualizes the radio field strength of the devices so that the communication network, KELGEN SD-Net, can be constructed quickly (**Fig. 12**). The radio field strength visualization software enables us to decide the repeater installation location while checking the radio field strength status of each device of the KELGEN SD and each repeater, thus enabling quick installation of the communication network, KELGEN SD-Net.

Transmission\ Reception	#C20154BB Receiver	#A2014815 Repeater #1	#A201484B Repeater #2	#A20149DE Repeater #3
#C20154BB Receiver	＼	107	99	97
#A2014815 Repeater #1	111	＼	120	107
#A201484B Repeater #2	98	117	＼	140
#A20149DE Repeater #3	94	101	137	＼

Fig. 12 Example of radio field strength measurement using radio field strength visualization software

The communication network of a KELGEN SD series product uses AES-128-compliant encryption to improve security.

10. KELGEN SDM (KSGD-SV data management)

The amount of power generated by KELGEN SD varies depending on the amount of heat energy from the environment. The KELGEN SD measurement interval is variable because the electricity storage time for one measurement session varies depending on environmental changes. In addition, data measured by IoT devices is accumulated in units of a few weeks or months, and its amount is very large. The highly difficult task of analyzing this irregularly acquired big data hinders the introduction of failure sign detection with IoT devices.

KELK has developed KELGEN SDM, which is IoT monitoring device verification evaluation software that has the function of primary processing KELGEN SD big data in an easy-to-process format and saving it by using spreadsheet software or BI tools. KELGEN SDM automatically saves the data processed by cleansing the raw data on an average for 1 minute as well as the KELGEN SD raw data. In addition, KELGEN SDM is provided with device information management and a simple visualization function; when detecting an abnormality that exceeds a preset judgment threshold, it emails the event to registered people responsible (**Fig. 13**).

KELGEN SDM assists in the visualization of irregularly acquired big data measured by the T/E EH monitoring device KELGEN SD and promotes the introduction of PdM.

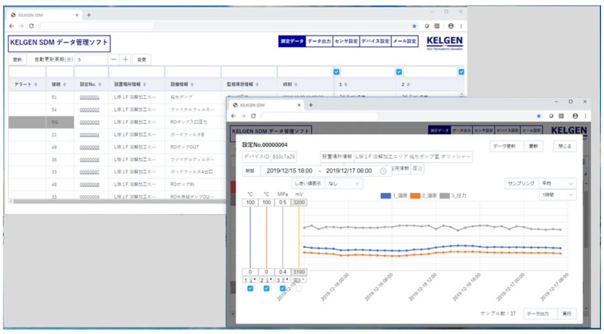

Fig. 13 Display screen of the KELGEN SDM visualization software section

11. KELGEN SD system

KELGEN SD, which operates by self-power generation by T/E EH, and a system that utilizes the measured data significantly reduce the installation and operational costs of the equipment failure sign detection system using IoT monitoring devices.

The KELGEN SD product group includes KSGD-ST, a T/E EH thermocouple monitoring device that measures the temperature of heat treatment furnaces and sintering furnaces, and KSGD-SA, a T/E EH analog input device that sends current and voltage values output from external output terminals such as existing flowmeters and pressure gauges, as well as KSGD-SV. All of these begin to operate at a temperature difference of 10°C and send measured data wirelessly.

The measured data sent wirelessly from KELGEN SD is collected by the communication network, KELGEN SD-Net. KELGEN SDM has a simple function saving KELGEN SD data and visualizing big data. The KELGEN SD series products assist in the introduction of PdM utilizing IoT monitoring devices.

Fig. 14 Overview of the KELGEN SD system

The KELGEN SD system has begun to undergo demonstration assessment as a failure sign detection system in production facilities of steel, automobile, and railway companies, as well as Komatsu plants.

12. Conclusion

KELK has improved the performance of the "T/E EH Vibration Monitoring Device KSGD-SV" to a practical level, which is a vibration sensor operating by T/E EH. We hope that the KELGEN SD system, which significantly reduces the installation and operational costs of failure sign detection monitoring device using IoT devices, will promote the introduction of PdM in the manufacturing industry and contribute to the improvement of productivity in Japan.

We also hope that T/E-EH-powered devices will enable more complex control and will be used in a wider range of fields thanks to technological advances such as improved T/E generation performance, reduced semi-conductor power consumption, and improved self-discharge of capacitors.

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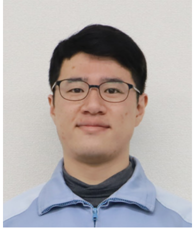

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[A comment from the authors]

We have succeeded in developing a practical level vibration sensor that operates by T/E EH. We would like to contribute to the realization of digital transformation (DX) in the Japanese manufacturing industry by improving the KELGEN SD series products so that users can master the IoT devices that monitor equipment.