Internet-based Remote Monitoring System of Thermo-Electric-Generations with Mobile Communication Technology

Dr. Wenjie Peng[a] and Professor Daizhong Su[b]

Advanced Design and Manufacturing Engineering Centre,
School of Architecture, Design and the Built Environment, Nottingham Trent University,
Nottingham, NG1 4BU, UK

[a]pengwenjie@msn.com [b]daizhong.su@ntu.ac.uk

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Abstract. A remote online condition monitoring system for Thermo-Electric-Generations (TEGs) is reported in this paper, which is applied in sustainable buildings. The system monitors the electrical power and heat energy generated by TEGs and to regulate the temperature of cold side of thermoelectric (TE) units used in the TEGs. The system provides the following major functions: data acquisition, data processing, system control and remote communication. The data acquisition module is built up within this system based on sensor technology and data I/O communication to acquire the data of working conditions of TEGs. System control is implemented by sending the commands to the control unit of the water valve for adjusting the temperature of cold side of TE units. The system has been validated by carrying out a case study of remote monitoring the working conditions of TEGs.

Biographical notes: Wenjie Peng received his PhD in 2011 and now works as a research fellow and part time lecturer in the Advanced Design and Manufacturing Engineering Centre, Nottingham Trent University. He has expertise in application of condition monitoring, Internet technology, wireless, mobile techniques and grid computing into engineering and sustainability. With such expertise, he has made successful contributions to several projects sponsored by East Midlands, EMDA sustainable Construction iNET, EU Marie Curie, FP7 cycLED, and FP7 Eco-Cost programmes.

Daizhong Su is Professor of Design Engineering and leads the Advanced Design and Manufacturing Engineering Centre at Nottingham Trent University, UK. His research interests include sustainable products development, sustainable buildings, integrated design and manufacturing, condition monitoring, and Web/Internet based engineering. His research has been supported by grants from various founding organisations including European Commission, UK research funding bodies, Royal Society, industries and international organisations. He is editor in chief of the International Journal of Design Engineering published by InderScience. He has been involved in organising more than 20 international conferences as Conference Chair, Co-chair, international chair and committee members. He has about 220 refereed publications.

Introduction

The research reported in this paper was conducted with the support of Sustainable Construction iNET High Education Institute Collaboration Fund, EMDA, UK, to develop a novel building block of thermoelectric co-generation for electricity and hot water[8] used in buildings The block uses heat energies from the exhaust gas of domestic boiler and solar radiation to generate electricity and also supply hot water for domestic use.

TEGs are made from thermoelectric modules which are solid-state integrated circuits that employ three established thermoelectric effects known as the Peltier, Seebeck and Thomson effects. It is the Seebeck effect that is responsible for electrical power generation. Their construction consists of pairs of p-type and n-type semiconductor materials forming a thermocouple. These thermocouples are connected electrically forming an array of multiple thermocouples (thermopile), and then sandwiched between two thin ceramic wafers. The energy from heat sources can be converted into electricity by such thermoelectric module in the presence of temperature difference [8] [9].

At present, there is nothing generally available in the market involving solar TEGs. Although currently PV systems are becoming dominated in the market, the costs are generally high and much dependant on silicon cells which result much CO_2 emission during the production [10]. The purpose is to make the TEGs device as simple and cost effective as possible to augment existing systems and be integral to an eco-structure, providing another source to make small efficiency improvements and to be deployable on mass scale.

The research reported in this paper is part of research project conducted by Nottingham Trent University (NTU) team, in collaboration with the project consortium members, University of Nottingham, and European Thermodynamics Ltd, a SME based on the Sustainable Construction iNET project. A remote condition monitoring system has been developed to monitor, control and record the working conditions of the TEGs. This paper details the development of remote condition monitoring system with emphasis on data acquisition, decision-making for system control, and mobile communication [1] [2].

Overview of the Remote Condition Monitoring System of Thermo-Electric-Generations

The remote condition monitoring system is developed in this research to monitor and control the working conditions of TEGs. The system utilises multiple sensors and data I/O interfaces to collect the data of working conditions from TEGs, and allows the users to access the working conditions data using mobile devices, such as mobile phones, via cellular phone network and Internet [3]. The system is able to automatically regulate the temperature of cold side of thermoelectric units used in TEGs to ensure that TEGs function to output electricity continuously. Figure 1 presents the overall structure of the remote condition monitoring system of TEGs.

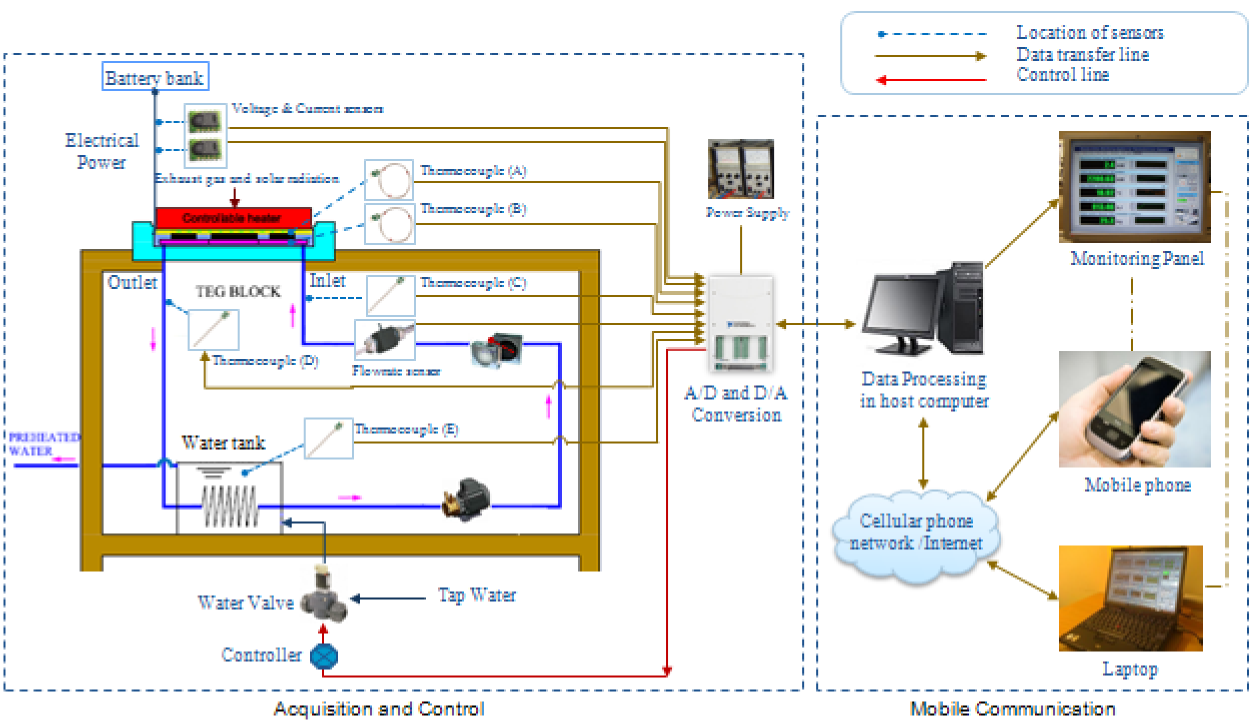

Figure 1 Structure of the remote condition monitoring system for Thermo- Electric-Generations (TEGs)

The remote condition monitoring system contains TEGs with thermoelectric units and a water supply unit, data acquisition and control units, a desktop computer as the server, a mobile phone with relevant software.

Thermoelectric units apply the thermoelectric effects, which converts temperature difference between the hot side and cold side into electricity [8]. When there is a temperature difference on both sides, thermoelectric units generate electrical power. The hot side of thermoelectric units is supplied with heat energy using the exhaust gas from domestic boiler and solar radiation; the cold side of the thermoelectric units remains cooling using the recycled water, which flows through the surface of cold side, and is supplied by the water supply unit connected with the cold side.

The water supply unit includes a tank, pipes, a pump, a water valve, and a tap associated with domestic water. The water stored in the tank is driven by the pump and flows in the pipes. On one hand, the water flows into the cold side of thermoelectric units via the inlet to absorb the heat energy, which is generated by thermoelectric effects of thermoelectric units; on the other hand, the heated water flows out of the cold side of thermoelectric units via the outlet and is subsequently sent back to the tank. The water temperature of the tank increases due to the effect of the returned heat water.

The water temperature of the tank has a significant effect on the cooling of the cold side of thermoelectric units. If the water temperature of the tank is extremely high, then the water flowing to the cold side of thermoelectric units is unable to satisfy the requirement of cooling-down of the cold side. Therefore, the water temperature of the tank must be low enough to ensure that the thermoelectric units functions in the normal condition. To resolve the above problem, the tap-water for domestic use will be injected into the tank to reduce the water temperature of the tank when the water temperature of the tank is over high and exceeds the upper limit set.

The amount of domestic water, to be injected into the tank, is controlled by a control unit, which manipulates the injection process of the domestic water by monitoring the water temperature of the tank and regulating the electric switch of the water valve. Once the water temperature of the tank is measured higher than the upper limit set, the water valve will be switched on and release domestic water into the tank immediately; meanwhile, the heat water in the tank will drain off the outlet of the tank. The drained water will supply its heat energy for domestic use, such as domestic heating [5]. The control method with regard to the water valve is detailed in section *'System Control'*.

The data of the working conditions of TEGs are acquired using thermocouples/sensors and data I/O interfaces [4]. Several thermocouples/sensors are set up in TEGs to collect the working condition data, such as temperature, water flow-rate, and output voltage/current. The thermocouples/sensors are located at the TEG's following positions: the hot/cold side of the thermoelectric units, the inlet/outlet of the cold side of thermoelectric units, the inside of tank water, and the positive/negative poles of the electricity generated by thermoelectric units, as shown in Figure 1. The thermocouples/sensors simultaneously acquire the working conditions data, and then transfer the data to the computer via the analogue/digital input interfaces. The method of data acquisition is presented in the section *'Data Acquisition'*.

The computer, as the system console, manages the process of monitoring and controlling the working conditions of TEGs. The computer processes the data of working conditions in real time, receives the control command from the operator/user, and regulates the operation of the devices/system. Also, the computer is used as the server to provide Web services for the communication with mobile phones.

The related application software has been developed using the following developing tools: (1) Labview Developer Suite, a graphical programming environment, to develop the server-end applications for data acquisition and decision making (system control); (2) Adobe Flex Builder, a programming development environment, to develop the user interface and script for remote communication with the server; (3) Flex Media Server (FMS), to build the media-driven code to transfer video stream from the computer to mobile devices in the client.

Technologies Applied in the Remote Condition Monitoring System

The remote condition monitoring system consists of the following four modules: data acquisition, data processing, system control and remote communication.

- **Data Acquisition**

Data acquisition module utilises the data acquisition unit to collect the data of working conditions from TEGs via the data I/O (Input/Output) interfaces. The data acquisition unit includes (1) five thermocouples associated with a signal conditioner, to acquire the temperature data of thermoelectric units, (2) voltage/current sensors, to measure the voltage and current of the electricity generated by thermoelectric units, (3) a flow rate sensor, to measure the flow rate of the water passing through the pipes, and (4) a data acquisition (DAQ) card with the data I/O interfaces that convert the received analogue data into the digital signal data and then transfer the data to the computer for further processing. Figure 2 presents the thermocouples and sensors, which are used for the measurement of working conditions data of TEGs.

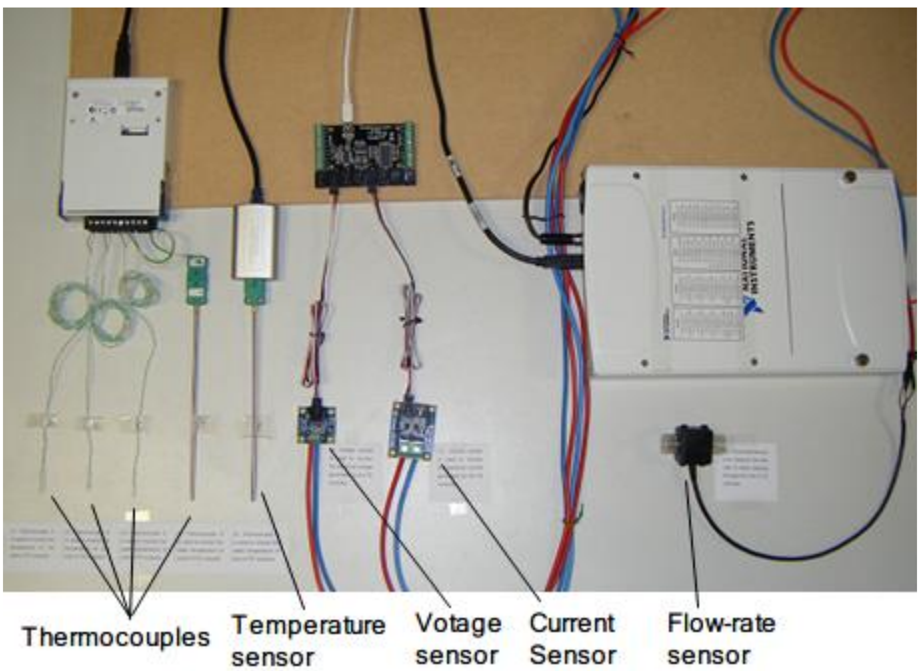

Figure 2 Data acquisition unit including thermocouples, sensors and data acquisition card

The acquisition of temperature data is conducted using the thermocouples with K-type miniature plugs/probes and a signal conditioner. The signal conditioner provides the temperature compensation for the cold-junction of the thermocouples, in order to ensure the accuracy of the temperature data measured; it is also applied for amplification and filtering of the low-voltage signals generated by the thermocouples. The application of the signal conditioner reduces the measurement error of the temperature data; the measurement error is less than 0.1% at 0-70 °C.

The high-precision voltage/current sensors and flow rate sensor are applied to measure the TEG's output voltage/current and the flow rate of water, respectively. The measured data are transmitted to the data acquisition card for further processing.

The data acquisition (DAQ) card uses data I/O communication interfaces, known as analogue input (AI) interface and digital counter (DC) interface, to transfer the acquired analogue/digital data which contain the physical information of working conditions to the computer for further processing.

The analogue input (AI) interface has the functions of the analogue input and differential calculation of signals; the sampling rate of the analogue input interface is 10 kHz and its data length is 100 per channel. The digital counter (DC) interface utilises the pulse counting method to collect data from a sensor. It has the capability of high-rate computation of data; the sampling rate of the digital counter is 80 kHz. In this research, the analogue input interface and the digital counter interface are used to transmit the output voltage/current, temperature, and flow rate to the computer in the digitised form.

- **Data Processing**

Data processing module is built to process the data, convert the data into the quantities of working conditions via A/D (analogue-to-digital) conversion, and display the data/results on a monitor panel.

In order to ensure the accuracy of the received data, the data are pre-processed in the following ways:
(1) The data are categorised into ten groups, and a group has 10 data.
(2) The data in each group are calculated to generate a root-mean-square (RMS) result;
(3) The mean of the RMS of ten groups is used as the data of working conditions at the time point.

The above method can get rid of the odd/invalid data and ensure that the calculation error is not more than 1%.

A/D conversion is applied to convert the data into the physical quantities of working conditions. Because the received data is not proportionally linear with the physical quantities of working conditions, non-linearization based A/D conversion is conducted.

Equation (1) presents the A/D conversion of temperature condition. Within the equation, the non-linearization calculation is conducted to convert the data into the temperature value [9].

$$\text{Temperature } (°\text{C}) = -2.0468 + 0.0367 * t - 1.5955\text{E-}6 * t^2 \quad (1)$$

where the item ‘t’ refers to the working condition data received from the thermocouple via the data acquisition card, and ‘Temperature’ is the temperature value gained using the non-linearization calculation.

The obtained temperature values are further calculated to acquire the following physical quantities: heat energy and electrical power generated by the TE units, and carbon dioxide emission saved.

Heat energy is gained with the following equation [10]:

$$Heat\ enegry\ (kJ) = c \times \rho \times G \times (T_{out} - T_{in}) \quad (2)$$

where, c is the heat capacity of water, 4.186kJ/kg°C, ρ is the water density, 1000kg/m^3, T_{out} is the water temperature of the outlet, T_{in} is the water temperature of the inlet, and G is the flow rate of water, m^3/s.

According to the mathematical model given by British Wind Energy Association (BWEA), carbon dioxide (CO_2) emissions saved is computed as follows [10]:

$$CO_2\ emission\ saved\ (kg / hour) = 0.035 \times Electrical\ energy\ (kW \cdot h) \quad (3)$$

where Electrical energy is gained using the product of the output voltage, the output current, and the time length of the duration of electricity.

The resulting quantities of working conditions are subsequently displayed on the monitoring panels as shown in Figure 3.

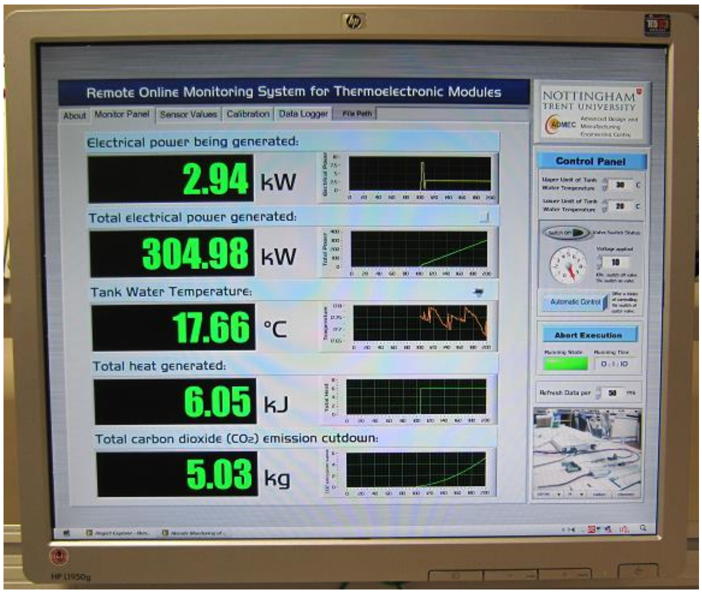

Figure 3 Real-time display of working conditions data in the primary monitoring panel

Figure 4 Real-time display of working conditions data in the secondary monitoring panels

The monitoring panels consist of the sub-panels, such as a primary panel and a secondary panel, which provide the real-time display of the following data/information:

(1) the working conditions data shown in the primary panel, including electrical power and heat energy generated by TEGs, CO_2 emission saved, and water temperature of the tank;

(2) the working conditions data shown in the secondary panel, including the temperature of hot/cold side of the thermoelectric units, the temperature of the inlet/outlet of the cold side of the thermoelectric units, output voltage and current, and flow rate of the water passing through the pipes;

(3) the parameters in the control panel, such as the upper/lower limit of the water temperature of the tank, to tune the switch of the water valve;

(4) the real-time video, to display the video/image of operation of the TEGs;

(5) A/D conversion parameters, such as the linearization coefficients and sampling rates of the system;

(6) data logger, to record the working conditions data of TEGs.

Figure 3 presents the monitoring interface of the primary panel, which displays part of working conditions data of TEGs as well as the time-waveform diagrams reflecting the relation between the working conditions and the time. Figure 4 shows the monitoring interface of the secondary panel, which displays the rest of the working conditions data of TEGs. The control panel located on the right of the primary/secondary panel, is used to configure the control parameters of the system/devices, and displays the system information, such as the operation status of the system, real-time video, etc.

- **System Control**

The control unit for regulating the switch of the water valve is designed to inject domestic water into the tank to decrease the water temperature of the tank. The control unit, shown in Figure 5, includes a data acquisition (DAQ) card for outputting analogue voltage signal, a DC current amplifier, and an electric switch associated with the water valve [1] [5].

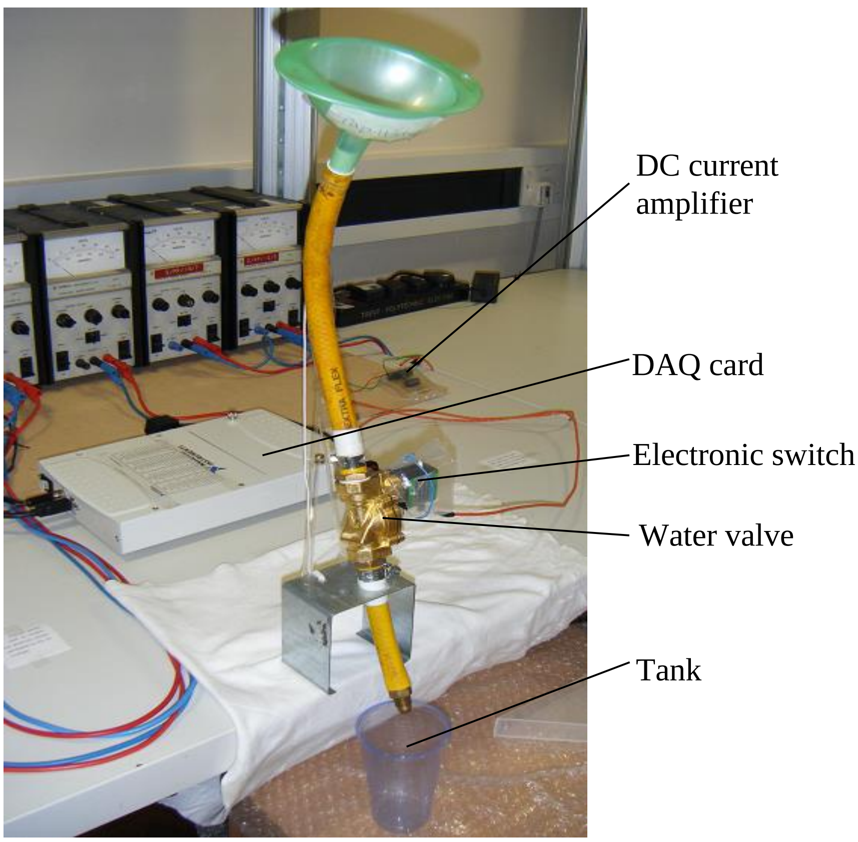

Figure 5 Control unit for regulating the water temperature of the tank

The DAQ card utilises the analogue output (AO) interface to convert the computer commands into analogue voltage signal, which is amplified by the DC amplifier and then transmitted to the electronic switch of the water valve. If the electric switch receives a high voltage such as 10V, then the valve will be switched on; if the electric switch is given a low voltage such as 0V the valve will be turned off.

The DAQ card is able to programmatically output the analogue voltage signal in the range of 0-10 volts to regulate the electronic switch of the water vale, according to the water temperature of the tank. When the water temperature of the tank is measured over the upper limit, the DAQ card outputs the high voltage signal to the electric switch; the valve is subsequently switched on and domestic water is injected into the tank. When the water temperature of the tank decreases below the lower limit set, the DAQ card outputs the low voltage signal to the electric switch; the valve is then switched off to stop the domestic water flowing into the tank.

The above control process can also be performed using a mobile phone. Since mobile communication has been applied as an important feature in this research, technicians/engineers who are in charge of the system are given the ability to remotely control the analogue output of the DAQ card and operate the switch of the water valve using mobile phones via the cellular phone network and the Internet. With regard to the control method using the mobile phone, please see section '*Remote Communication*' for more details.

In order to secure the devices/system in the control process, a self-protection mechanism is built up within this module. The self-protection is implemented by real-time monitoring the water temperature of the tank and the voltage applied on the electronic switch. In case that the water temperature of the tank is measured extremely high and cannot be adjusted to the normal conditions, the mechanism of self-protection will be triggered automatically. With the effect of this mechanism, the thermoelectric units and water supply unit will stop working. In the meantime, a warning message will appear on the monitor panel to alert the engineer/technician the current operation status of the system.

- **Remote Communication**

The remote communication module utilises the wireless-based server-client networking structure to realise the communication between the server and the client. During the communication, Web Service is deployed in the server and is responsible to receive the request from the client. While the user send a request with the control commands to the server via Internet/cellular phone network, Web Service is able to make a quick response by passing the request to the system modules such as data processing/acquisition module for further processing; according to the request received, the system modules conduct the classification and calculation, and then send the commands to the control units to perform the required operation or control tasks. In the meantime, the working condition data of the TEGs are acquired via the data acquisition unit and are transmitted to the monitor panels for real-time display [6] [7].

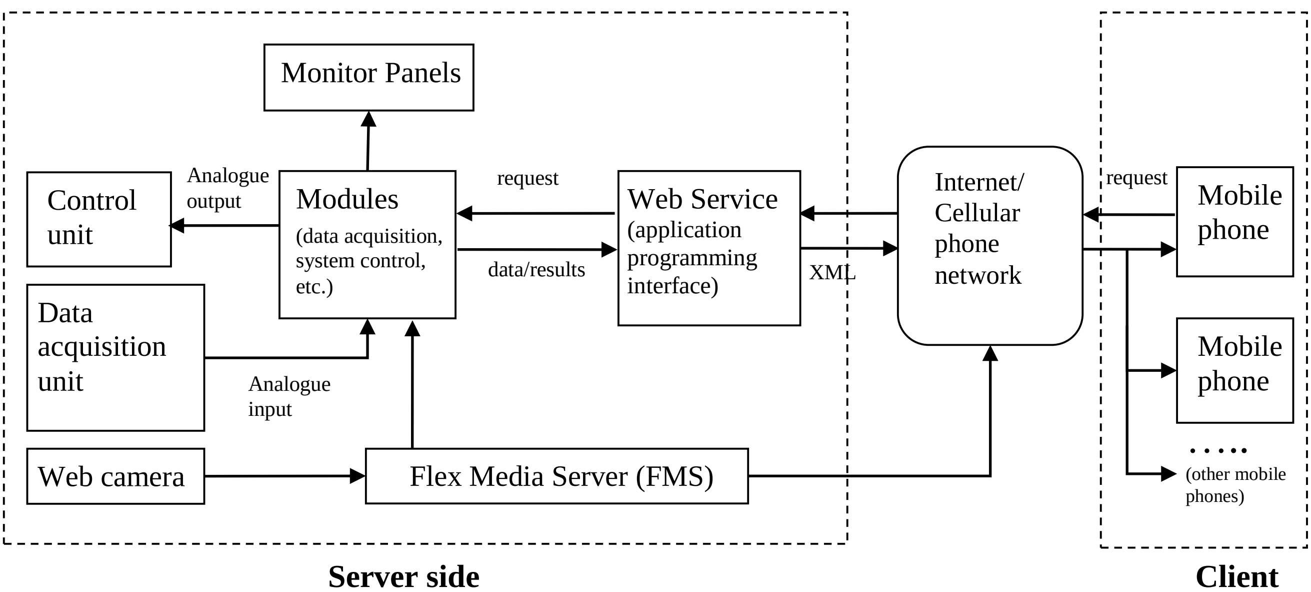

Figure 6 Structure of remote communication between the server and the client using the Internet, cellular phone network, and mobile phones

As the response to the client-end user, the working condition data are to be sent to the client in form of XML (Extensible Mark-up Language) via Internet/cellular phone network. XML is an efficient and reliable data-carrier, which is used in Web Service and conveyed over the Internet, and allows the data to be converted into the standard Web form and transferred to the client.

Figure 6 shows the remote communication between the server and the client using Internet and cellular phone network. The server-client network including a server computer and client-end mobile phones is detailed in the following sub-sections.

- **Server Side**

The server is located beside the TEGs and connected with the Internet. It includes a server computer, a monitor panel, a Web camera, and a network interface for the communication with the client. The Web camera is used to capture the video/image of work of the TEGs.

The server computer has the functions of real-time data acquisition/processing, system control, and the communication with the client-end mobile phones. The above functions are implemented using the server software which is developed by Labview Developer Suite.

The server software contains several programme blocks; each programme block performs an independent function, e.g. data acquisition, A/D conversion, D/A control and data transfer over the Web. These programme blocks utilise the uniform computer/networking resources, such as network ports, transmission protocols, and application programming interfaces, and transfer the data/information each other.

Among the programme blocks, the network-based shared variables (GSV) are applied to transfer different types of data, such as two-dimensional waveforms graphs and tables. As an important feature/function used in Labview, GSV can effectively transmit data/information to a specific interface of the server, i.e. application programming interface (API), for the communication with the client.

The application programming interfaces, Google API and Web Service, are used to create a remote connection between the server and the client. Google API enables the server to transmit the measurement data to a network disk of Google, so that client user is able to access those data over the Internet anytime. When the user wants to control hardware devices located at the server, Web Service provides the real-time online connection, which allows for the client user to access the server and control the devices remotely. Web Service secures the communication between the server and the client, and ensures the compatibility of different computer languages/platforms.

The implementation of the Web Service starts by processing the data to the XML form. Using the following Labview XML syntax, the data/information, such as working conditions data, and system message and parameters, can be written as the XML code.

```
<?xml version='1.0' standalone='yes' ?>
<Heading>
    <Record_1>
       <Val>
          data_1
       </Val>
    </Record_1>
    <Record_2>
       <Val>
          data_2
       </Val>
```

```
		</Record_2>
		<Record_3>
		……
	</Heading>
```

Within the XML syntax, ‘data_1’ and ‘data_2’ refer to the data/information to be written into the XML. The tags <Record_1> and </Record_1> are used to define a record with ‘data_1’; the tags <Record_2> and </Record_2> use the same method to define a record for ‘data_2’. The tags <Heading> and </Heading> specify a heading of the XML code including all the records.

Using the above syntax, the data/information is encoded to the XML, which is then transmitted as a response to a data buffer in memory using the Response function of Labview. When the server receives a user request from the client, the response, i.e. the XML code, which remains in the data buffer, will be sent to the client.

The real-time video/image, to monitor the work of the TEGs, is also to be sent to the client together with the working condition data. The video is acquired by the Web camera and then processed by Flex Media Server (FMS), which encodes the captured video to stream data and broadcast it to the client. The process of publishing and transferring the stream data to the client is programmed using the MXML language in Adobe Flex builder.

- **Client Side**

The client allows many users to access the server to acquire the information concurrently, such as data, graphs, tables and a video, using mobile phones via the cellular phone network and the Internet. It also allows an authorised user such as a technician to log into the server as an administrator to control the operation of the TEGs by delivering requests with control commands to the server. Such the control method facilitates the technician to remotely examine /assess the functionality and reliability of the system.

The client software, including user interfaces and script, is developed using Adobe Flex Builder and Open-plug programming environments. The user interfaces are applied to display the data of the working conditions of TEGs, such as the electrical power, heat energy, and output voltage/current. The user interfaces also allow the user to configure the information required for accessing the server and to set up the parameters related to the control of the devices/system.

The script, which is closely connected to the user interfaces, is responsible to deliver the data/results received from the server to the user interface for the display, and, meanwhile, to send the user requests including the system parameters and control commands to the server.

The communication with the server is implemented by Web Service, which is the same as the application programming interface of the server. On one hand, the client sends requests with commands/parameters to the server via Web Service; on the other hand, the client retrieves responses from the server in XML form, and then resolves the responses to display the data/results on the user interface.

Case Study - Remote Condition Monitoring using Mobile Phones via the Internet and GPRS Mobile Phone Network

The developed remote condition monitoring system has been applied to monitor and control the working conditions of TEGs used in an experimental environment, as shown in Figure 7. The mobile phones, such as Nokia, HTC, and iPhone mobile phones, are applied in the client to wirelessly access the working conditions data of TEGs from the server. In the case shown below, a Nokia phone is used to demonstrate the major functions of the system, while, at the end, brief illustrations are also given to show the HTC and iPhone applications.

The data acquisition hardware contains five K-type thermocouples associated with a signal conditioner, a voltage sensor, a current sensor, a flow rate sensor and a DAQ card. The sensors and thermocouples are set up to monitor the working conditions data, such as output voltage, output current, temperature and flow-rate of water.

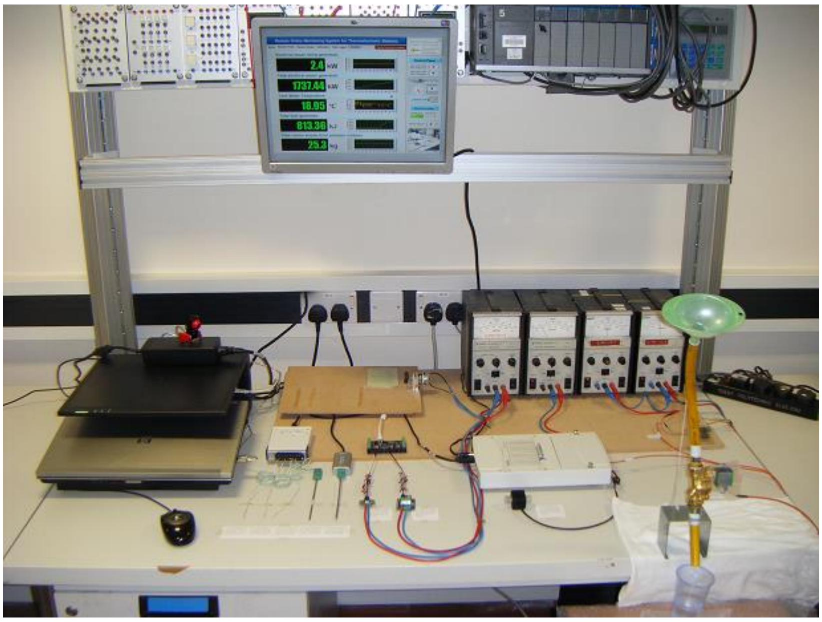

Figure 7 Remote Condition Monitoring of Thermo-Electric-Generations used in an Experimental Environment

The DAQ card has the dual functions of data acquisition and control. On one side, the DAQ card acquires the data of working conditions from the TEGs via the thermocouples and sensors, and then transfer the data in digitised form to the computer for data processing and decision making. On the other hand, the DAQ card converts the control commands of the system into the analogue output signal which is then transferred to the controlled device, such as the electric switch of the valve, to conduct the required control output.

(a)

(b)

Figure 8 Remote acquisition of working condition data from different monitor panels of the server computer using Nokia mobile phone

When the system was in operation, the working conditions data were displayed on the monitor panel of the server computer in real time. Using Nokia N900 mobile phone (smartphone), the user accessed the server computer via the GPRS cellular network and the Internet to retrieve the working condition data, which were then displayed on the user interface of the mobile phone. Figure 8 presents the real-time acquisition of working condition data of TEGs using Nokia mobile phone. It is observed from the Figure 8(a) that the water temperature of the tank was 17.71°c, which was lower than the upper limit set.

By sending the requests to the server via the mobile phone, the user can access the working condition data from different monitoring panels of the server computer. Figure 8 (a) and (b) shows that the user utilised Nokia mobile phone to receive the working conditions data from the server's the primary panel and secondary panel, respectively.

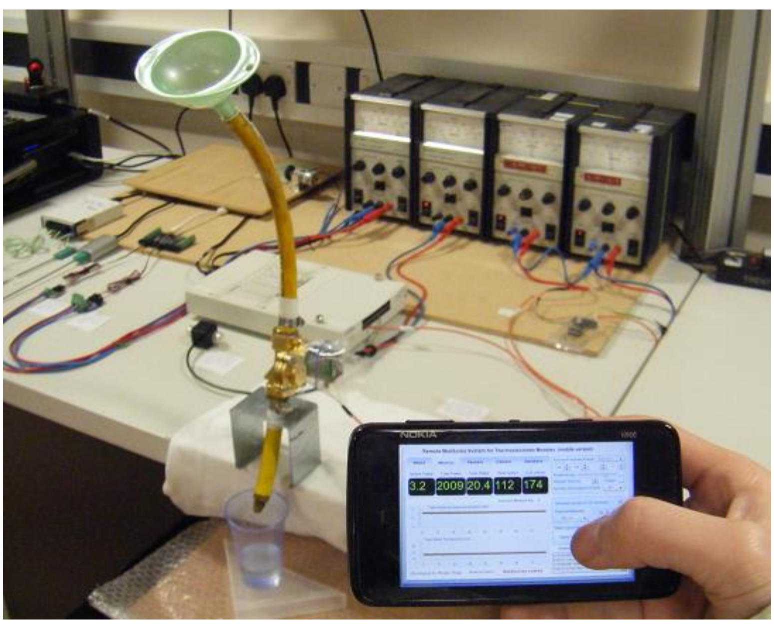

Figure 9 Remote control of the electric switch of the valve using Nokia mobile phone

When the water temperature of the tank increased and was measured higher than the limit set, the commands for switching on the water valve were activated in the server and automatically sent to the DAQ card, which then transmitted the analogue signal with high voltage to the electric switch of the valve. Subsequently, the valve was switched on and domestic water was injected into the tank to reduce the water temperature of tank; meanwhile, the heat water in the tank was drained off the tank via the outlet. When the water temperature of the tank dropped down below 20°C, the valve was switched off with the effect of the shutdown command of the system.

Although the adjustment of working conditions of TEGs is able to be performed by the system automatically, the technicians/engineers, in some circumstance, need to remotely examine and assess the quality and reliability of the control system. To meet such the requirement, the system allows the authorised user to log into the server as the diagnostician, who can adjust the control parameters of the system to regulate the working conditions of TEGs.

Within the user interface of the mobile phone, the parameters/commands of the system control include 'Step control', 'Switch of the valve (On/Off)', 'Upper/lower limit of the water temperature of the tank', etc. These parameters/commands allow the user to remotely control the electric switch of the valve using mobile phone. When 'Step control' was Enable and 'Switch of the valve' was on, the electric switch associated with the valve was open immediately and then the domestic water was injected into the tank, as shown in Figure 9. While 'Switch of the valve' was off, the water valve was shut down to stop the injection of water. While 'Remote Video' was enabled in the mobile phone, the video for monitoring the operation of TEGs was broadcasted to the Nokia mobile phone, as shown in Figure 10.

Multiple mobile phones can be used to access the working conditions data from the server. Furthermore, mobile cross-platform communication enables the mobile devices with different cellular phone operation systems to access the server concurrently. Figures 11 and 12 present the remote acquisition of working conditions data from the primary/secondary panel of the server using HTC mobile phone, respectively. Figure 13 presents the real-time monitoring of working conditions using iPhone mobile phone.

Figure 10 Real-time display of the video which monitors the operation of TEGs using Nokia mobile phone

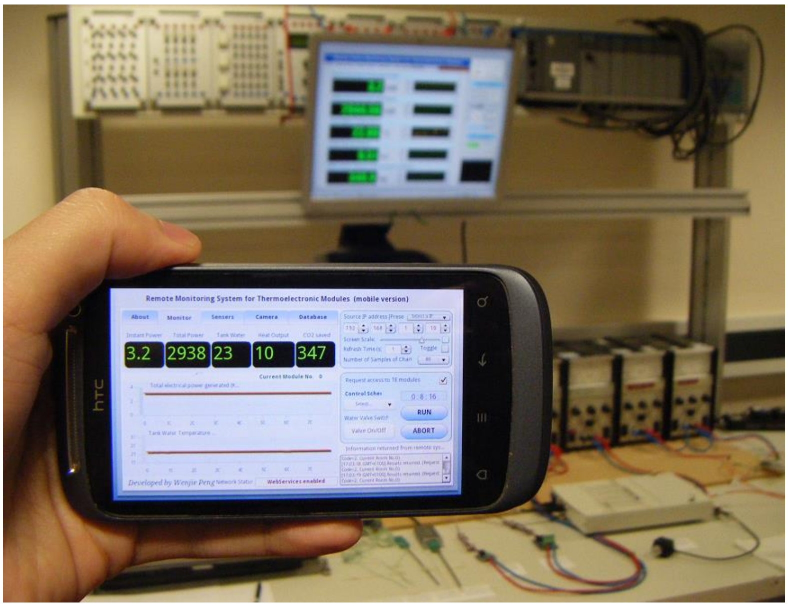

Figure 11 Remote acquisition of working condition data from the primary panel of the server using HTC mobile phone

Figure 12 Remote acquisition of working condition data from the secondary panel of the server using HTC mobile phone

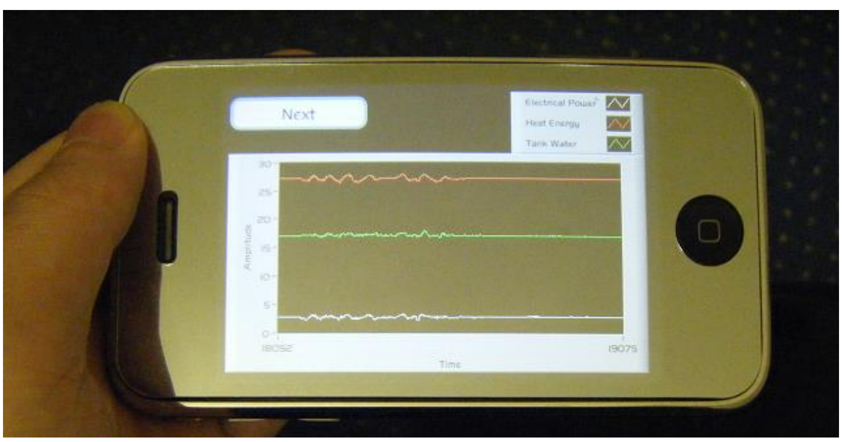

Figure 13 Real-time acquisition of working conditions data of TEGs using iPhone mobile phone

Conclusions

At present, there is nothing available in the market involving solar Thermo- Electric-Generations (TEGs). Therefore, the remote online condition monitoring of TEGs is significantly innovative application. In this research, the remote online condition monitoring system has been successfully developed and applied to monitor and control the working conditions of TEGs. The users are able to utilise smartphones, such as Nokia, HTC and iPhone, to access the data of working conditions and control the operation status of TEGs via Internet and GPRS cellular phone network. Temperature control of the cold side of thermoelectric units used in TEGs is performed automatically under the control of the server system.

The MySQL-based database is established to store the working conditions data in the server computer. The database allows the user to acquire the current/history data of working conditions using the ODBC (open database connectivity) via the Internet and/or the mobile phone network. Experimental result validates the success of the system which is able to effectively monitor the actual working conditions of TEGs and maintain the operation of the system in real environment.

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