온도센서를 이용한 전력설비의 온라인 상태 감시

論 文
57P-2-24

On-Line Condition Monitoring of Electrical Equipment Using Temperature Sensor

崔 龍 成† · 金 宣 在* · 金 榮 敏** · 宋 煥 基*** · 李 炅 燮§
(Yong-Sung Choi · Sun-Jae Kim · Yeong-Min Kim · Hwan-Kee Song · Kyung-Sup Lee)

Abstract - Condition monitoring technologies allow achieving this goal by minimizing downtime through the integrated planning and scheduling of repairs indicated by condition monitoring techniques. Thermal runaways induced by conduction problems deteriorate insulating material and cause disruptive dielectric discharges resulting in arcing faults. Therefore, having the ability to directly measure the temperature of the contacts while in service will provide more information to determine the true condition of the equipment. It allows corrective measures to be taken to prevent upcoming failure. Continuous temperature monitoring and event recording provides information on the energized equipment's response to normal and emergency conditions. On-line temperature monitoring helps to coordinate equipment specifications and ratings, determine the real limits of the monitored equipment and optimize facility operations. Using wireless technique eliminates any need for special cables and wires with lower installation costs if compared to other types of online condition monitoring equipment. In addition, wireless temperature monitoring works well under difficult conditions in strategically important locations. Wireless technology for on-line condition monitoring of energized equipment is applicable both as stand alone system and with an interface for power quality monitoring system. The paper presents the results of wireless temperature monitoring of electrical equipment at a power plant.

Key Words : On-Line Temperature Monitoring, Wireless Sensor, Thermal Failure, Event Recording, Electrical Equipment

1. Introduction

The ability to continuously monitor the condition of energized equipment (on-line monitoring) enables operation and maintenance personnel with a means to determine the operational status of equipment, to evaluate present condition of equipment, timely detection of abnormal conditions, and initiate actions preventing upcoming possible forced outages[1]. The consequences of such faults are serious enough to justify the efforts to build a temperature monitoring system to protect electric facilities from disaster.

Continuous temperature monitoring of energized equipment provides true information about the condition of the equipment while in service compared to testing the different parameters during preventive maintenance (PM) cycles. Generally speaking, physical conditions of electrical contact may display different values and trends depending upon measurement conditions. For example, the most common technique of determining the quality of contact condition today is measuring the contact resistance while applying 100V to the primary path.

Needless to say, in real life when the same contact is exposed to thousands of amperes of alternating current, it may behave very differently. For example, some of the laboratory tests demonstrated that high contact resistance during the test does not lead to overheating when in service, due to the presence of films on the contact surface with non-linear resistance values [2-4]. On the other hand, a loose, "hand-tight" connection could easily pass the Contact Resistance Test. Therefore, having the ability to directly measure the temperature of the contacts while in service will provide more information to determine the true condition of the equipment. Corrective actions could be performed only when a degraded condition requires maintenance, thus reducing the time and cost of PM testing.

Continuous temperature monitoring will identify potential problem areas that can lead to substantial equipment damage. Correlation between the temperature measurement, and load and ambient conditions would allow abnormal

† 교신저자, 正會員 : 東新大學校 電氣工學科 敎授 · 工博
E-mail: yschoi67@dsu.ac.kr
* 正 會 員 : 世宗大學校 나노工學科 敎授 · 工博
** 正 會 員 : 全南道立大學 消防安全管理科 敎授 · 工博
*** 正 會 員 : (株)龍山電力 代表理事
§ 正 會 員 : 東新大學校 電氣工學科 敎授 · 工博
接受日字 : 2008年 4月 21日
最終完了 : 2008年 5月 16日

conditions to be identified and early alarms to notify operation and maintenance personnel of a potential problem. Further deterioration of the condition could lead to a recommendation to take the equipment out of service for repair and maintenance. The real value of the on-line monitoring is not in setting off multiple alarms but in triggering the maintenance events leading to a true condition based maintenance, and providing the key answers to implementing the plant assets management.

Continuous monitoring of the thermal condition would allow for optimization of the equipment's operation. The real limits of the monitored equipment would be determined by measuring temperatures in correlation to the load information and event recording. Present industry standards include a set of rules and tables to define and limit the overload condition of the equipment while in service. These requirements are somewhat restrictive and conservative. They leave a lot of "gray areas" and questions and the user is often advised to "contact the manufacturer of the equipment". During the recent testing on a medium voltage circuit breaker, we discovered that 30% overload for 3 hours did not cause the temperatures of the contact points to rise above the limits allowable by the standard. At the same time, the application standards would not allow such a condition and would require a lengthy cooling cycle.

The real effect of loading can be only determined by the actual temperature measurement. The paper presents the results of wireless temperature monitoring of distribution equipment at a power plant. The real effect of loading can be only determined by the actual temperature measurement. This is especially important for equipment and systems that have been in service for several years. Taking into account the ambient temperature and the allowable maximum temperature rise of the component specified in equipment standards, the monitoring of the current path temperature may allow system operation personnel to overload the equipment above the rated continuous current.

2. Experiment

Way to monitor temperature using infrared emission of a heated surface is to monitor temperature with non-contact IR thermometers. IR sensors are installed in close vicinity to the target and send signals to a remote PC [4]. An optimal distance between the sensor and target is determined by the size (diameter, D) of the target and parameters of the sensor. For each type of IR sensor, the ratio FOV (Field of View) = X/D is a constant value where X is the distance between the sensor and the target. The smaller the target area (D), the closer to the target the sensor should be. This condition contributes to limited applications and targets of interest. Another downside of using IR non-contact sensors is the need to run the cables from each sensor to the receiving units.

The most important advantage of using wireless technology for monitoring the thermal condition of energized equipment is eliminating cables and wires from the system. Another important benefit of wireless technology is much lower installation costs than other types of online monitoring equipment [5-7]. Wireless systems work well in difficult or dangerous-to-reach locations or in moving applications. An ideal wireless temperature monitoring system (WTMS) consists of the following components.

2.1 Hardware

A. Sensors

- sensor : IR sensor (TP1) (wireless communication method : RFID)
- wireless units equipped with unique identification;
- sensing units built from miniature and dielectric components;
- signal transmissions from multiple sensors do not interfere with each other;
- units are installed at the key points on the equipment in limited space;
- sensing units may have one of the following power sources:
  - * power supply such as battery
  - * self-powered by the alternating magnetic field of a bus bar
  - * remotely powered

B. Receiver or interrogator

- installed at a significant distance from the sensors in the central location;
- collects data from all sensors;
- works independently in series with other receivers;
- easily recovers from temporary electromagnetic interference;
- transfers the data to PC

2.2 Software

- Service software is able to receive, process and present the data transferred from receiver in user-friendly format, and to issue pre-alarm and alarm signals to the customer either locally or via Internet.
- Analytical diagnostic software provides tools to not only locate the source of temperature rise, but also to determine what type of change in physical conditions of apparatus led to heat runaway. In other words, the diagnostic software would be able to determine whether

there is a surface decay, mechanical deterioration, or lack of sufficient airflow inside a cubicle (or a combination of the causes) resulting in heat runaway.

- Analytical prognostic software provides tools, which will determine what kind of actions should be planned in condition based maintenance (CBM) based on diagnosis and issue recommendations on the actions for the user to undertake in regards of CBM.
- Analytical optimizing software addresses the issues of optimized operation of the system in regards to reconfiguration of the loads due to the various ambient conditions, equipment location and conditions, or modification of the overloading profile (emergency loads for critical applications during the power consumption peaks), providing effective asset management.

Some other benefits in effective Wireless Temperature Monitoring System are:

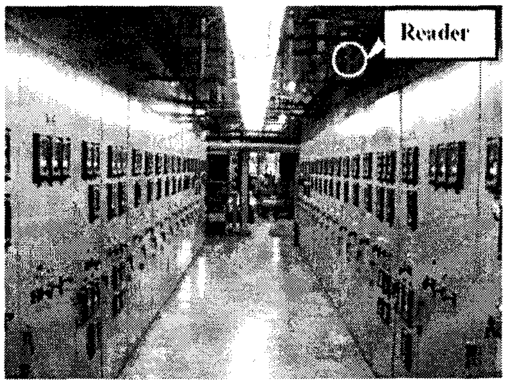
- Low installation costs
- Easy-to-use product
- High reliability, minimum defects, low maintenance
- Compatibility with existing products
- Long service life

Two versions of a temperature monitoring system may be used. A stand-alone system provides the delivery of data from a receiver to a local PC. The temperature information is then processed for visual representation (graphical or tabular) by software, which also issues audio and video alarms as soon as temperature of a particular point reaches a pre-determined level. This type of system provides reliable continuous monitoring of thermal conditions of electrical units. Another version of a temperature monitoring system having an interface with power monitoring system provides continuous monitoring of both temperature and power quality through a web-based server is presented.

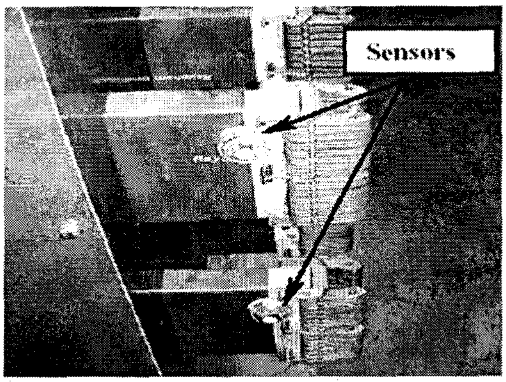
The Wireless Temperature Monitoring System has been installed at one of the power plants at a large utility (Fig. 1 (a)), which suffered multiple violent thermal failures on main breakers. The goal was to use the temperature sensors to continuously monitor temperature while the breakers are under load. The stand-alone system is able to provide warning alarms as soon as the temperature of the points where sensors are installed reaches a pre-determined level. Wireless temperature sensors have the following parameters:

- uniquely identified sensing units are built from miniature and dielectric components and operate in direct contact with the surface;
- sensors are calibrated in wide temperature range: from -0 ℃ to 150 ℃ (for outdoor applications sensors are calibrated from -40 ℃ to 85 ℃);
- transmittance intervals are based on the rate of a temperature change: signal is sent every minute at temperature rising for 3℃ per minute and once in 3 minutes at stable temperature (battery life saving mode);
- Sensing units use a small coin battery as a power source; minimum battery life 5 years, typical 7-10 years, easily changeable.

Miniature wireless sensors have been installed at all six panels (FC) (Fig. 1 (b)) of four MV circuit breakers, two of which (main breakers) are continuously under load. Two other breakers are used as reserve. Every cell is also equipped with a sensor on the internal wall to measure temperature of the ambient air within the cell. One reading device installed in the control room receives RF signals with information about the location and temperature of each point where the sensors are installed (there are a total of 28 transmitters). This information is continuously transferred from the Reader to the local PC located in the operator room and connected with a reading device via communication cable. The temperature data is continuously collected in the database and analyzed together with load data to determine any abnormalities in temperature behavior.



(a) Switchgear with Temperature Monitoring System Installed at Power Plant.



(b) Wireless Temperature Sensors on panel.

Fig. 1 System configuration.

Two other breakers are used as reserve. Every cell is also equipped with a sensor on the internal wall to measure temperature of the ambient air within the cell. One reading device installed in the control room receives RF signals with information about the location and temperature of each point where the sensors are installed (there are a total of 28 transmitters). This information is continuously transferred from the Reader (Fig. 1 (a)) to the local PC located in the operator room and connected with a reading device via communication cable. The temperature data is continuously collected in the database and analyzed together with load data to determine any abnormalities in temperature behavior.

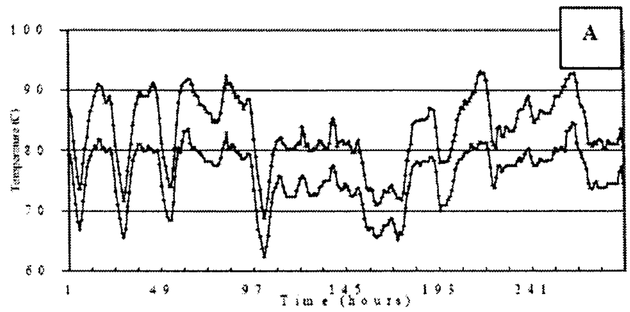
3. Results and Discussion

3.1 On-Line Wireless Temperature Monitoring

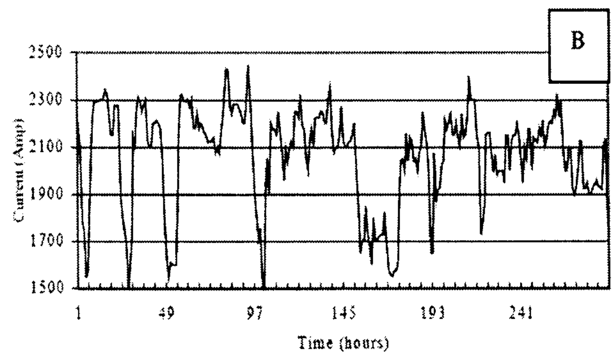
Through temperature monitoring and data analysis, the normal heat distribution within the cell and temperature of panels (depending on the location within the cell) was determined. The change of panel temperature (Fig. 2 (a)) follows every increase and decrease of the current (Fig. 2 (b)) with very short delay (minutes). The shape of the temperature curve is very similar to that of the load, copying even minor changes of the current.

The temperature of the top and bottom FCs on Phase A and C are very close. The difference in temperature between Phase B and Phases A and C is usually in the range 5-10 ℃. After one month of monitoring, the first warning signal was an observation of a very high temperature of the ambient air within the main cells. It was reaching 60 ℃ even though the current was well below the maximum rated current for the breakers. As a result, the temperature on the finger clusters occasionally reached 100 ℃, which is very close to standard maximum for current-carrying parts of MV circuit breakers (105 ℃) (Fig. 3, A). It was determined that the elevated temperature within the cells was caused by a poor ability to evacuate heat build-up. The existing switchgear did not provide louvers on the doors and no forced ventilation within the cells.

It was strongly recommended to improve ventilation within the cells, which was done with minimum expense. An opening was made in the door of the cell with two small vents installed to increase airflow inside the cell. The result was very promising: temperature of the air within the cells dropped an average 10 ℃ for the same current accompanied with the corresponding drop of the temperature on all six finger clusters (Fig. 3, B). This drop in temperature provided a large and safe temperature margin for the load on the main circuit breakers.

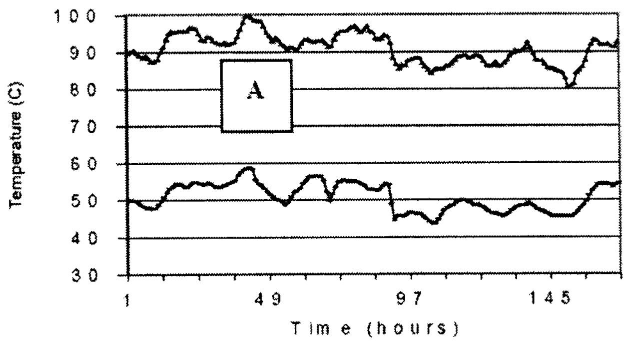


(a) Temperature

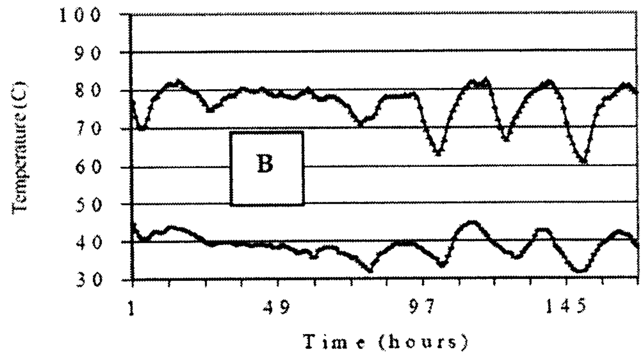


(b) Current

Fig. 2 Temperature (A) on Top FC of Phase A and B and Load (B).



(a) Without ventilation



(b) With forced ventilation

Fig. 3 Ambient temperature (bottom curve) and on B Phase Top FC (top curve) in the same cell without ventilation (a) and with forced ventilation (b).

After data collection and data analyzing, a very unusual abnormality has been detected on one of the phases. The temperature has suddenly risen 10-15 ℃ on Phase A's finger clusters and they become as hot (or hotter) as the FCs on Phase B. The temperature rise usually happened when the load rose (Fig. 4).

Six such events have been observed on one main breaker during one year of temperature monitoring. Duration of the rise varied from 40 to 400 hours. Since temperature rises have been within standard limit (< 65 ℃) during these events, the Temperature Monitoring System issued no alarms.

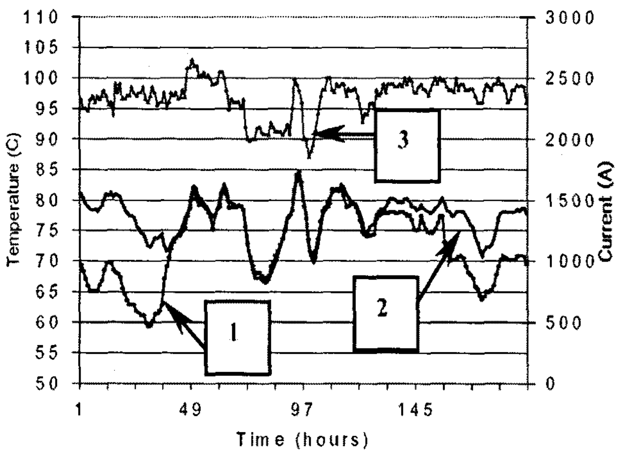


Fig. 4 Temperature growth on Phase A (1) compared with that on Phase B (2) and current (3).

This thermal event on one of the phases affected heat distribution within the cell, leading to significant deviations from normal thermal behavior. The temperature rise on Phase A is accompanied with temperature change on Phase C (Fig. 5), so the top FC becomes warmer than the bottom FC, which is opposite to normal temperature distribution within the cell. The cause of these temperature abnormalities is not yet determined. Plant personnel have been warned about these events and asked to perform inspection of the unit at the earliest convenience.

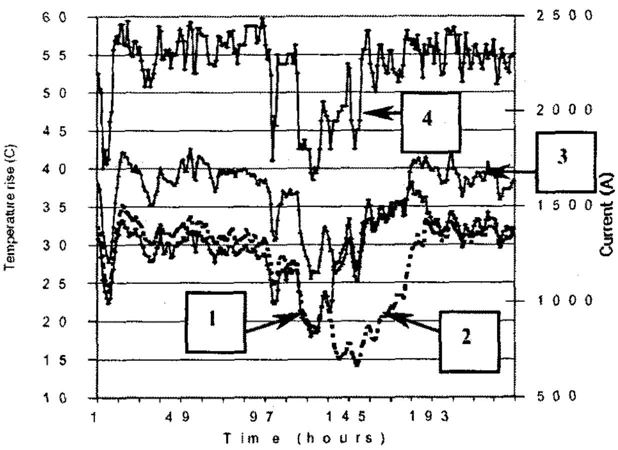
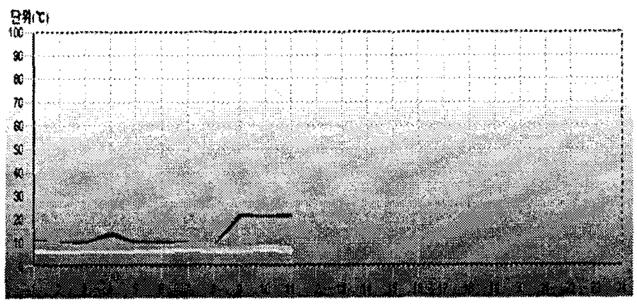
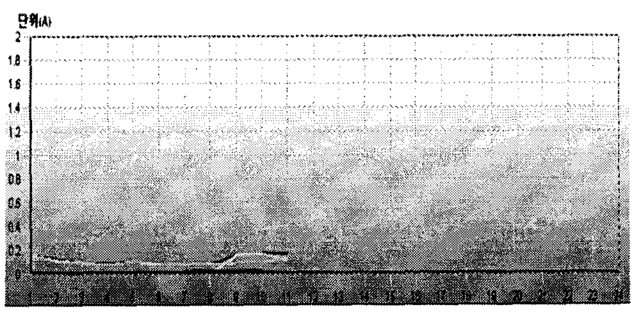


Fig. 5 Thermal abnormality on Phase A effects heat distribution within the cell: temperature rise for Top FCs on Phases A (1), B (2) and C (3), and load (4).



(a) Temperatures



(b) Currents

Fig. 6 Real Time Trends - graphical representation.

3.2 Web-based Server for On-line Wireless

Real-time trend feature allows building graphical representation for live temperature data coming from wireless sensors over the provided period of time with a fixed update rate (Fig. 6, A). Multiple points can be displayed which provides for easy visual representation of temperature trends. Such trends are useful when they are allowed to run for longer periods of time and are compared to each other, for example trends for temperatures and currents (Fig 6, B). Users benefit from this feature by setting the threshold feature and getting the visual conformation of goals for the points monitored. It allows also detecting any discrepancies in behavior of different quantities.

Another feature worth noting is an ability to create "live" trends (Fig. 7) with the real-time point information. These trends can be easily created by an end-type user with a number of standard objects, allowing displaying meters, value bars and blocks, conditional graphics, image backgrounds, etc. The drawings can be linked to each other, allowing browsing them once they have been designed.

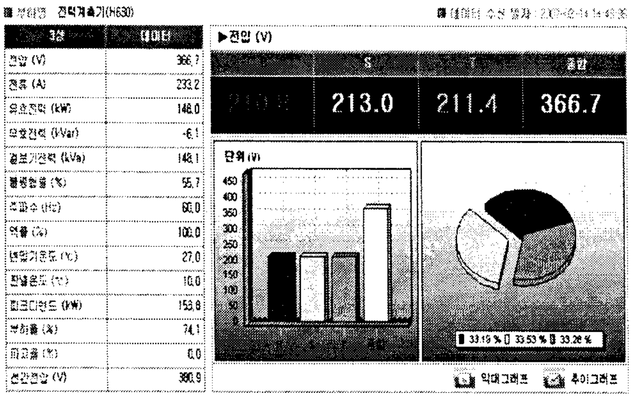


Fig. 7 Real Time Trends (live trends).

A series of alarms can be created based on the points from the monitored devices. Such alarms can warn users of abnormal thermal conditions on a single device level or a combination of thermal conditions based off information from several devices. The alarms can be produced visually, as well as audibly. An additional feature allows e-mailing or sending a page to pre-selected recipients with the alarm's time and description.

4. Conclusions

Continuous temperature monitoring of energized equipment provides true information about the condition of the equipment while in service. The benefits of wireless online temperature monitoring are:

1. Wireless temperature monitoring system can be easily applied to existing power equipment. The wireless technology allows installation of the Temperature Monitoring System on existing equipment with short interruption in service. The monitoring system provides accurate measurements and consumes as little power as possible to ensure long operating life.
2. The wireless sensors can be used throughout a facility without any limitation to the type of equipment to be monitored. This finally would provide a universal tool to manage and control various assets. The sensors may be installed on motors, transformers, panel boards, and switchgear as well as on boilers, pipes, PC boards, air compressors, etc. In other words, such monitoring system would become a key component in asset management.
3. Wireless temperature monitoring system provides information on the condition of power equipment, which facilitates planned maintenance and decreases downtime, and increases the reliability and availability of power equipment. Based on information available online and real-time, equipment operators could use it to make system restoration decisions after an interruption, or possibly even prevent an interruption by removing a distressed apparatus in a controlled manner.

Acknowledgement

This work was financially supported by MOCIE program (R-2007-2-234-01).

References

[1] Jeffrey H. Nelson. "Electric Utility Consideration for Circuit Breaker Monitoring", Proceedings of the 2001 IEEE/PES Transmission and Distribution Conference and Exposition, Oct 28-Nov 2, pp. 1094-1097 (2002).

[2] Denis Koch, Ruben Garson. "Square D Type FB4 SF6 Circuit Breaker Contact Resistance", Minutes of the Sixty-First Annual International Conference of Doble Clients, p. 5-6.1-5-6.19 (1994).

[3] Wayne W. Manges, Glenn O. Allgood, and Stephen F. Smith It's Time for Sensors to Go Wireless, Part 1, Technological Underprints, *Sensors*, April (1999).

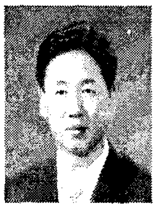
[4] Glenn O. Allgood, Wayne W. Manges, and Stephen F. Smith. It's Time for Sensors to Go Wireless. Part II. Take a good technology and make it an economic success. *Sensors*, May, pp. 70-80 (1999).

[5] Wayne. W. Manges, Glenn O. Allgood, Stephen F. Smith, Timothy J. McIntyre, and Michael R Moore, Eric Lightner. "Intelligent Wireless Sensors for Industrial Manufacturing, *Sensors*, April (2000).

[6] Christopher McLean and Dave Wolfe, Intelligent Wireless Condition-Based Maintenance, *Sensors*, June (2002).

[7] Darragh Maxwell and Russell Williamson. Wireless Temperature Monitoring in Remote Systems, *Sensors*, October (2002).

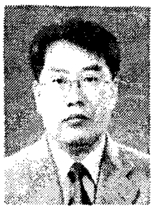
저 자 소 개



최 용 성 (崔 龍 成)

1967년 11월 14일생. 1991년 동아대학교 전기공학과 졸업 (학사). 1993년 동 대학원 전기공학과 졸업 (석사). 1998년 동 대학원 전기공학과 졸업 (공박). 1999년~2001년 JAIST Post-Doc.. 2001년~2003년 Osaka Univ. Post-Doc.. 2002년~2005년 원광대학교 연구교수. 2006년~현재 동신대학교 전기공학과 교수. 2006년~현재 전력산업인력양성사업단 기획운영부장.

Tel : 061-330-3204
Fax : 061-330-3103
E-mail : yschoi67@dsu.ac.kr



김 선 재 (金 宣 在)

1986년 서울대학교 금속공학과 졸업 (학사). 1988년 한국과학기술원 재료공학과 졸업 (석사). 1992년 한국과학기술원 재료공학과 졸업 (공박). 1992년~2001년 한국원자력연구원 선임연구원. 2001년~현재 세종대학교 나노공학과 교수. 2001년~현재 나노신소재공동연구소 소장.

Tel : 02-3408-3780
Fax : 02-3408-3664
E-mail : sjkim1@sejong.ac.kr

김 영 민 (金 榮 敏)

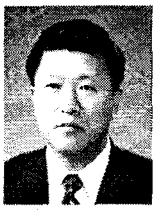
1968년 2월 10일생. 1989년 전북대학교 전기공학과 졸업 (학사). 1991년 동 대학원 전기공학과 졸업 (석사). 1996년 동 대학원 전기공학과 졸업 (공박). 1998년~현재 전남도립대학 소방안전관리과 교수. 2004년~2005 전남도립대학 기획홍보실장. 2005년~2005년 전남도립대학 도서관장.

Tel : 061-380-8622
Fax : 061-380-8469
E-mail : ymkim@namdo.ac.kr

송 환 기 (宋 煥 基)

1952년 1월 20일생. 1990년~현재 (주) 용산전력 대표이사. 2006년~현재 한국전기전자재료학회 광주전남지부 부지부장.

Tel : 062-962-7400
Fax : 062-962-7402
E-mail : ecag112@hanmail.net



이 경 섭 (李 炅 燮)

1956년 11월 09일생. 1983년 조선대학교 전기공학과 졸업(학사). 1986 동 대학원 전기공학과 졸업(석사). 1991년 동 대학원 전기공학과 졸업(공박). 1988년~현재 동신대학교 전기공학과 교수. 1994년~ 1995년 동경공업대학 객원연구원. 2006년~현재 전력산업인력양성사업단 단장.

Tel : 061-330-3203
Fax : 061-330-3103
E-mail : kslee@dsu.ac.kr