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# A SULPHUR HEXAFLUOROIDE GAS LEAKAGE DETECTION SYSTEM USING WIRELESS SENSOR NETWORKS

# SISTEM ODKRIVANJA UHAJANJA PLINA ŽVEPLOVEGA HEKSAFLOURIDA Z UPORABO BREZŽIČNIH SENZORSKIH MREŽ

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**Keywords:** sulphur hexafluoride gas, $SF_6$, circuit breakers, gas leakage, WSN

## Abstract

Most high-voltage (HV) transformer stations currently use sulphur hexafluoride ($SF_6$) gas as a dielectric to prevent arcing in circuit breakers. The excellent dielectric properties of $SF_6$ allow HV equipment to be constructed in only 10–20% of the volume/space of air insulation. Reductions of $SF_6$ gas density in circuit breakers cause failures in providing the required interrupter insulating properties and can lead to operational inefficiencies and safety hazards. $SF_6$ has a global warming potential 23,900 times that of $CO_2$; therefore, any leakages must be strictly monitored. The most fundamental measure against the uncontrolled emission of the $SF_6$ gas into the atmosphere is the constant monitoring and detection of its leakage in energy facilities. The methods for the $SF_6$ leakage detection should be extremely precise, while simultaneously having acceptable implementation costs. This paper presents a solution for an $SF_6$ gas monitoring system using Wireless Sensor Network (WSN) nodes. These nodes use multi-hop networking to transmit data to a base station connected to the other stations and the internet through a secure VPN (Virtual Private Network) connection. Using wireless sensing systems also significantly decreases installation time and reduces costs of materials and labour.

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## Povzetek

Večina visoko napetostnih transformatorskih postaj trenutno uporablja plin žveplov heksaflourid (SF6) kot dielektrik, ki preprečuje preboje v odklopnikih. Odlične dielektrične lastnosti plina SF6 dovoljujejo visokonapetostni opremi, da je konstruirana le z 10-20% prostornine zračne izolacije. Zmanjšanje gostote plina SF6 v odklopnikih povzroča napake v zagotavljanju zahtevanih izolacijskih lastnostih naprave in lahko vodi k operativni neučinkovitosti ter ogroža varnost. SF6 ima veliko večji vpliv na globalno segrevanja (23900-krat večji od CO2), zato mora biti kakršnokoli puščanje nadzorovano. Najosnovnejši ukrep pred nenadzorovanimi emisijami plina SF6 v ozračje je konstantno spremljanje in zaznavanje puščanja plina v energetskih objektih. Metode detektiranja puščanja plina SF6 morajo biti izredno natančne, istočasno morajo imeti tudi sprejemljive stroške izvedbe. Članek predstavlja rešitev za nadzor količine plina SF6 z uporabo vozlišč v brezžičnem senzorskem omrežju. Ta vozlišča uporabljajo omrežje z mrežno topologijo za prenos podatkov do bazne postaje, ki je povezana z ostalimi postajami. Prav tako uporabljajo internetno povezavo s pomočjo vzpostavljene VPN povezave (virtualno privatno omrežje), ki omogoča dostop do skupnega omrežja preko varne neposredne povezave. Uporaba brezžičnih senzorskih sistemov bistveno zmanjša čas montaže in stroške materiala ter dela.


# 1 INTRODUCTION

The key role of $SF_6$ gas in circuit breakers is to extinguish electrical arcs when contacts inside the circuit breaker are pulled apart. $SF_6$ has a global warming potential of 23,900 times that of $CO_2$ (compared over a hundred year period). $SF_6$ is also a highly stable gas, and its atmospheric lifetime is 3200 years. Therefore, working with $SF_6$ gas has to be strictly monitored. The most fundamental measure against the uncontrolled emission of the $SF_6$ gas into the atmosphere is the constant monitoring and detection of its leakage in energy facilities. The methods of leakage detection should be extremely precise (enabling the detection of extremely low concentrations of the $SF_6$), while simultaneously having acceptable implementation costs.

The downside associated with the installation of $SF_6$-insulated switchgear has been the lack of diagnostic equipment able to establish the integrity of the insulating gas, which is a necessity considering the severe and costly damage that can occur if the unit suffers an in-service failure. This problem can be overcome by utilizing wireless sensor technology for monitoring transformer stations and substations. This could produce significant benefits for power utility companies. The wireless sensor network (WSN) can be used for monitoring the condition of critical and expensive equipment in transformer substations, which has many advantages in comparison to existing monitoring systems. Every sensor node should be protected with a metallic cover due to the high-voltage environment. The nodes use multi-hop networking to transmit data to a base station, which also should be protected. The base station is connected to the other stations and the internet through a secure VPN connection. Depending on their specific application, sensor installation nodes may have an autonomous power supply (long lasting batteries, solar power with rechargeable batteries) or use the external power available at the transformer substation. Using wireless sensing systems also significantly decreases time and reduces the costs of materials and labour.

A WSN based on sensor nodes equipped with sensors for the detection of $SF_6$ gas can be the core of a state-of-the-art $SF_6$ monitoring and leakage detection system. Through the gateway, the WSN is connected to the local area network (LAN) and to the internet (optional possibility). Therefore, the information obtained from the sensors can be available worldwide. Such an approach is more precise and less expensive in comparison to conventional wired methods. Moreover, it is more reliable, more flexible and easily extended.

The prototype WSN for $SF_6$ detection is based on Crossbow's MICAz wireless sensor nodes extended with $SF_6$ detectors. The standard for wireless communication between nodes is 2.4 GHz ZigBee (IEEE 802.15.4). The sensor network is connected to the local area network through the NB100 Stargate NetBridge gateway. Due to multiple points of $SF_6$ leakage detection, such a system is tolerant on failures of certain sensor nodes.

In the following section, the role of $SF_6$ gas in circuit breakers is described in detail. The environmental impact of $SF_6$ gas leakage is depicted in Section III, while proposed system for $SF_6$ gas leakage detection system is described in detail in Section IV. Section V gives the conclusion.

## 2 THE ROLE OF $SF_6$ IN CIRCUIT BREAKERS

In a transformer substation, a key element is the high voltage circuit-breaker (CB). Its role is to open and close the generator, transformer, and distribution transmission line terminals in order to protect electrical equipment against overload and short circuit currents. A prerequisite for the basic operation of a circuit breaker is excellent arc quenching for switching. This is realised using $SF_6$ gas.

$SF_6$ gas is used inside circuit breakers to extinguish the electrical arc when contacts inside the circuit breaker are pulled apart, thus enabling the electrical circuit to be broken. The excellent dielectric properties of $SF_6$ allow HV equipment to be constructed in only 10–20% of the volume/space compared to air insulation. Gas amounts can vary between a few to 300 kg $SF_6$ per gas compartment. $SF_6$ circuit breakers are closed pressure systems, which means that the $SF_6$ gas under pressure is closed in the tank, and its volume is replenished only periodically by manual connection to an external gas source. The equipment can only function properly if no or only minimal emissions of $SF_6$ exist; therefore, keeping the gas sealed is a basic issue. Reduction of $SF_6$ gas density in circuit breakers causes failure to provide required interrupter insulating properties and can lead to operational inefficiencies and significantly reduced safety.

The main causes of serious faults in CB, i.e. failures with interruptions to service, are identified as the operating mechanism failure and leakage of the insulating medium $SF_6$. This gas is increasingly used in the high-voltage electrical industry because it is an excellent dielectric, has an exceptionally strong electrical arc switching characteristic, and is chemically inert, non-toxic and non-flammable. At present, there is no known dielectric and breaking agent better than $SF_6$ gas, so there are no viable alternatives to it in the high-voltage electrical industry.

The use of $SF_6$ technology results in compact equipment with low material usage, high operational safety, minimized fire load and high availability. There is also a positive ecological balance because of lower energy losses compared to conventional AIS solutions (therefore, it contributes to $CO_2$reduction).

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# 3 ENVIRONMENTAL CONCERNS RELATED TO $SF_6$ GAS

The Kyoto Protocol designated $SF_6$ as a greenhouse gas (GHG) whose release to the atmosphere needs to be limited. The Global Warming Potential (GWP) of this gas is 23,900 greater than that of $CO_2$ 1, so it can contribute to the man-made greenhouse-effect, if it is released into the atmosphere. $SF_6$ is also highly stable gas, and its atmospheric lifetime is 3200 years. Consequently, awareness of the climatic effect of $SF_6$ became common after 1995, and since then the usage of $SF_6$ gas has been given increasing attention. Practical productions require correspondence with European Regulators' Group for Electricity and Gas, Smart Metering with a Focus on Electricity and Gas Regulation [1].

To the year 2002, it is estimated that $SF_6$ had contributed only 0.28% of total EU-15 greenhouse gas emissions (Figure 1), [2]. $SF_6$ emissions from electrical power equipment contribute less than 0.05% to the total European GHG effect, [2]. Because of high expected future rates for $SF_6$ use, significant efforts have been made in recent years to implement emission reduction measures dedicated especially to fluorinated gases. The level of emissions over the expected CB lifetime of 40 to 50 years depends on specific design elements of the equipment and the production process, but also on lifetime maintenance requirements, $SF_6$ handling equipment and procedures. From the mid-1990s onward, manufacturers and users active began reducing and controlling emissions. Many efforts are being made to reduce the emission of $SF_6$ to the lowest level possible during the life cycle of the circuit breaker, from the development phase, the manufacturing process, then during its service life, particularly during maintenance and at the end of life of the equipment.

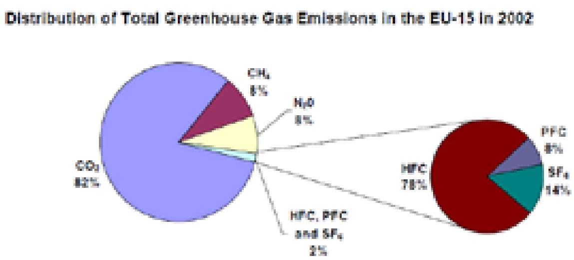


***Figure 1:*** *The rate of $SF_6$ in total EU-15 greenhouse gas emissions in 2002, [2]*

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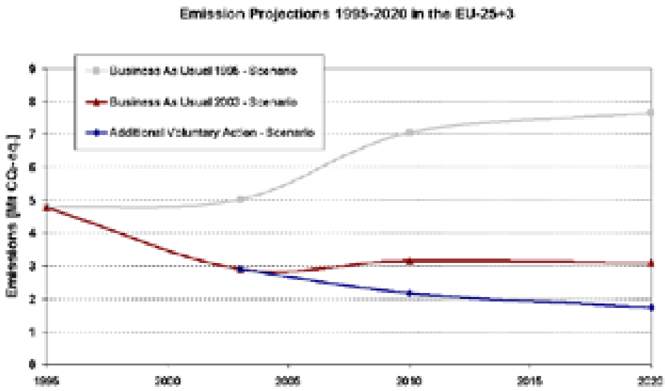


***Figure 2:*** *Emission projections 1995-2020 for three Scenarios, [2]*

Owing to the continuous improvement of products (more compact, lower emission, low leakage rates during the lifetime of the equipment) in that period, leakage rates for new equipment are below 0.5% p.a. for closed pressure equipment. This made it possible to introduce the IEC 62271-1 standard in 2004, which states that maximal leakage can be 0.5%/p.a. However, a large number of older circuit breakers that were not produced according to such a standard remain; their condition has to be monitored.

Despite better characteristics of new circuit breakers, according to [2], $SF_6$ emissions were projected to rise after 2003 without further action by manufacturers and users due to strong bank growth. Therefore, further European & global realization of emission reduction is necessary.

Volunteer actions of manufacturers and users (utilities) of electrical high and medium voltage equipment in Europe realized a reduction of 40 % $SF_6$-emission from 4,8 Mt $CO_2$-eq in 1995 to 2.9 Mt $CO_2$-eq in 2003 (see Figure 2) by improved handling of $SF_6$ throughout the lifecycle of SF6-equipment including manufacture, use and end-of-life, despite a significant increase of the bank of SF6 in electrical equipment.

For the HV sector using $SF_6$-filled HV electrical equipment, there is neither a restriction nor any limitation to the use of $SF_6$ in electrical equipment above 1000 V. That is because $SF_6$ is characterized by excellent insulation and arc quenching with no equivalent at the moment. Efforts to find alternative fluids for $SF_6$ of the same functionality, but less overall environment impact have not been successful. However, there is a reduction of losses in the HV power network as an indirect effect of $SF_6$-insulated equipment, because one ton of installed $SF_6$ in HV applications would save 0.8 GWh per year, which also means a reduction $CO_2$ emissions. The EU-F-Gas-regulation intends to ensure that blue scenario from Figure 3 is met.

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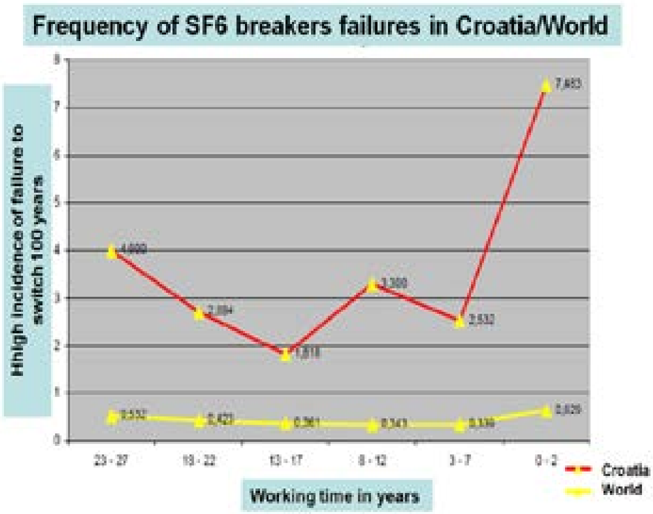


***Figure 3:*** *$SF_6$ Breakers failures in Croatia/World*

Regarding the reliability data for Croatian power system components in 2004–2008 period, the circuit breakers have average frequency of failures f = 2.877 for 1/100 pieces a year. This is the highest value for frequency failures among all components. There is total of 830 breakers in HV transmission network in Croatia, among which are approximately about 400 $SF_6$ circuit breakers. Improving their reliability using WSN $SF_6$ leakage detector monitoring will have significant influence on overall reliability of the Croatian power system and in reducing electrical power outages to the consumer on the 110 kV voltage level.

## 4 WSN MONITORING SYSTEM FOR $SF_6$ LEAKAGE

Networks of sensors are widely used for monitoring and control applications. In a communication network, deployment of wires is expensive and can cause problems during normal operations and maintenance. Wireless sensor networks efficiently eliminate the need for wires, but also open many new application domains. Reliability and low-power consumption are the two key factors that determine the performance of a WSN. Collecting and delivering $SF_6$ gas sensor data over a wireless sensor network is a convenient way to automate older high voltage substations without requiring expensive and invasive retrofits. WSN technology could enable a wide spectrum of other functions at substations to be remotely monitored at a reasonable cost.

Leaks of $SF_6$ gas are rare, but effectively detecting and preventing them has clear benefits for the environment, as well as for improving system reliability and performance through reduced maintenance costs and the prevention of costly equipment failures. The utilization of wireless sensor technology for monitoring transformer stations and substations could produce significant benefits for power utility companies.

The sensor nodes use multi-hop networking to transmit data to a base station, which should also be protected. The base station is connected to the other stations and the intranet through

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the secure VPN connection. Wireless sensors can be used for monitoring many different parameters. One example of potential usage is the monitoring of transformer surface temperatures or surface temperatures of the circuit breakers in order to detect anomalous or fault conditions. They can also be used for the detection of transformer bushing degradation by detecting phase differences between the obtained voltages. Wireless sensor nodes can also be equipped with mechanical, acoustic or chemical sensors for monitoring vibrations, acoustic discharge sensing and detecting certain chemicals in the air, such as fumes and other dangerous gases. Depending on their specific application, sensor nodes may have autonomous power supply (long-lasting batteries, solar power with rechargeable batteries) or use the external power available at the transformer substation. Using wireless sensing systems also significantly decreases installation time and reduces costs of materials and labour.

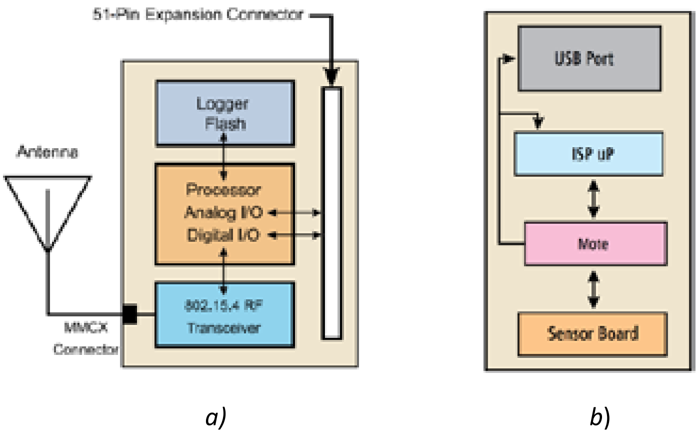


***Figure 4:*** *a)WSN Block Diagram; b) Programmable Base Station*

The recently developed technology of wireless sensor networks has immense potential for the use in power transformer stations for $SF_6$ leakage detection. The nodes of a wireless sensor network include adequate sensors, a data processing unit, a wireless communication subsystem and the battery power unit. Such sensor nodes are low-power and low-cost devices capable of mutual wireless communication with the base station.

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The prototype of wireless sensor network for $SF_6$ gas detection is based on Crossbow's MICAz wireless sensor nodes extended with the $SF_6$ sensors. The standard for wireless communication between nodes is 2.4 GHz ZigBee (IEEE 802.15.4). The maximum packet size supported by 802.15.4 is 128 bytes, and the maximum raw data rate is 250kbps. Power consumption of the proposed system is as follows: Processor- 8mA under load, 15µA in sleep; Radio- 27111.4 transmit, l0mA receive, lµA sleep; expected lifetime is 1 year on AA batteries; Operating system- TinyOS.

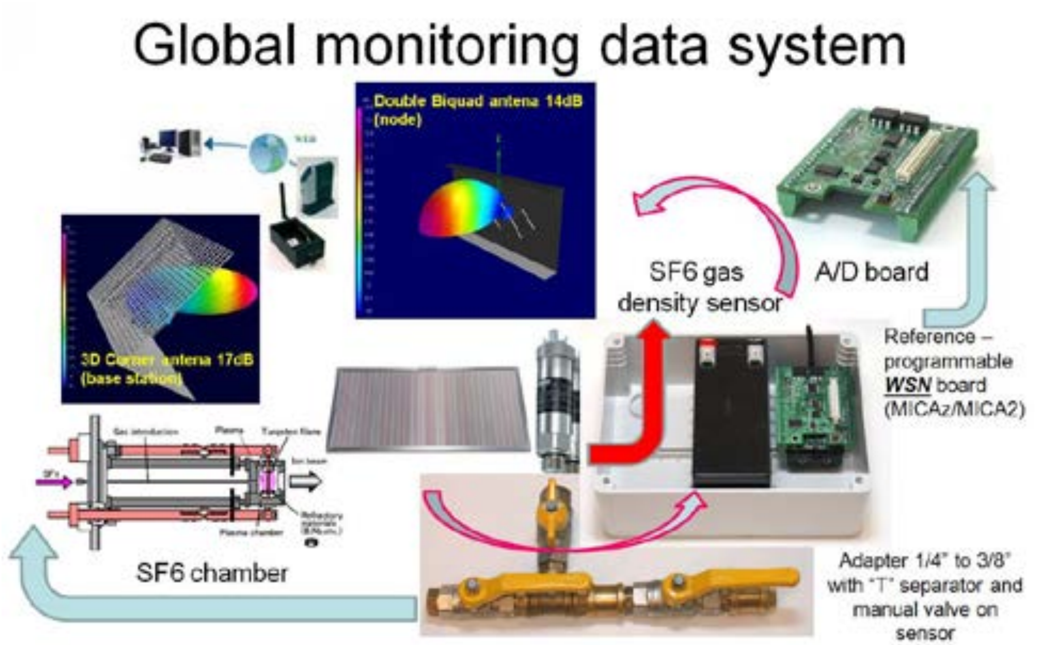


***Figure 5:*** *Monitoring the leakage of $SF_6$ gas from the chamber, [3]*

The sensor network is connected to the local area network through the *NB100 Stargate NetBridge* gateway. Due to multiple points of $SF_6$ leakage detection, such a system is tolerant of failures of certain sensor nodes.

The development of the custom-designed sensor application is enabled through *Crossbow's MoteWorks* software platform, which allows programming sensor nodes via the programmer or via a remote computer over the supervisory. A local database allows *XServe* (internal application) to store and process sensor network information. *XServe* effectively bridges these different realms through the support of standard XML APIs.

Figure 5 shows the remote monitoring system realized using a wireless sensor node extended with an MDA300 data acquisition board. A mechanical T-divider is envisaged for combining the monitoring system and circuit breaker chamber, and also for chamber replenishment. The mechanical valve setup ensures the protection of the sensor during the chamber replenishment and provides a sensor replacement with minimal $SF_6$ leakage. Since the sensor requires an additional power supply, the system includes a solar panel connected to a battery and control circuitry. Besides the analogue input for data about $SF_6$ density (adc0 channel), other analogue channels (adc1 and adc2) serve for the battery voltage measurement and charging. The calculation of the Rs (shunt resistance) gives the electric current signal termination on MDA300 board. The linearization of input measures was performed with the polynomial integration in firmware. Such linearization is an element for future work. Standard antennas provide a range of approximately 70 meters, while setup of double-bi-quad and 3D corner antennas provided larger coverage.

The principle of the sensor is based on the two chambers, of which one is the reference and the other the measurement chamber, [5]. The difference in the resonant frequencies in the chambers (vacuum and $SF_6$) is manifested as a current (*I [mA]*) signal through the DC–DC converter. The current size is the main measurement that defines the density and the pressure in the chamber.

The development of custom sensor applications is enabled through Crossbow's *MoteWorks* software platform, which is specifically optimized for low-power battery-operated networks and provides support for sensor devices, server gateways and user interface. The server gateway is based on middleware (*XServe*) for connecting wireless sensor networks to enterprise information and management systems. *XServe* is the glue layer that connects the wireless sensor network to enterprise or industrial networks through standard XML. Due to the low-power and memory footprint requirements in wireless sensor networks, communication is streamlined through message formats and network protocols.

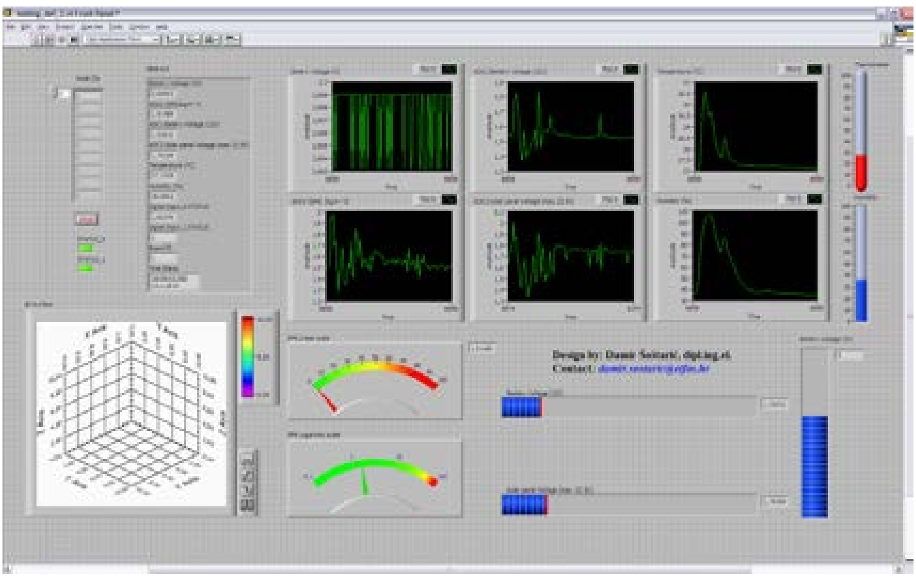

***Figure 6:*** *An example of user interface for $SF_6$ monitoring based on MICAz with data acquisition board MDA 300 and National Instruments LabView 2011, [6]*

This differs from the IP protocols used in IT back-end systems or existing industrial networks. XServe effectively bridges these different worlds through the support of standard XML APIs. A local database allows XServe to store and process sensor and network information. Integration with back-end monitoring, control and management systems delivers the full value of wireless sensor networks to enterprises and makes the connection of the physical world with the internet a reality.

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The user interface for the Crossbow platform can be *MoteView* or a third party product like *LabView* (Figure 6) functioning as a client application for remote analysis, monitoring, management and configuration of the sensor network. Standardized interfaces should allow easy system upgrading.

# 5 CONCLUSION

Wireless sensor networks can be used for monitoring the condition of critical and expensive equipment in transformer substations, providing many advantages in comparison to existing monitoring systems. These advantages include lower installation costs and utilization of the distributed processing capabilities of the wireless sensor nodes to provide smarter sensing mechanisms, [8]. Certainly, the great advantage of wireless sensing technology is the elimination of the risks of on-site data collection from the high-voltage substation. Wireless sensor nodes can be equipped with different types of sensors and deployed throughout the station to monitor different critical parameters. Every sensor node should be protected with a metallic cover due to the high-voltage environment. Existing solutions based only on pressure measurement are not sufficiently precise, [7]. There are approximately 400 $SF_6$ circuit breakers in the HV transmission network in Croatia. Improving their reliability using WSN $SF_6$ leakage detector monitoring will have significant influence on overall reliability of the Croatian power system and on reducing un-supplied electrical energy to the consumer on 110 kV voltage level. In reference to the future system functionality, the system could be extended to additional sensors in WSN, for example accelerometer/gyroscope in three axes, ultrasound, vibration sensors (in terms of strain gauges) etc.

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