FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 30, N° 1, March 2017, pp. 107 - 119
DOI: 10.2298/FUEE1701107N

INDUSTRIAL WIRELESS SENSOR NETWORKS AS A TOOL FOR REMOTE ON-LINE MANAGEMENT OF POWER TRANSFORMERS' HEATING AND COOLING PROCESS

Aleksandar Nikolić[1], Nataša Nešković[2], Radoslav Antić[1], Ana Anastasijević[2]

[1]University of Belgrade, Electrical Engineering Institute Nikola Tesla, Serbia
[2]University of Belgrade, School of Electrical Engineering, Serbia

Abstract. *Industrial Wireless Sensor Network used for supervising of high power transformer cooling system is presented in the paper. Due to the fact that in the thermal power plant where industrial prototype is installed is very noisy environment, a lot of problems should be solved in order to obtain high reliability and accuracy of the system. Results of the analysis presented in paper are obtained from the real thermal power plant where presented wireless sensor network based on-monitoring system is used for continuous management of power transformers' heating and control of their cooling systems. Obtained results during system operation in longer period confirm its stability, accuracy and improvement in power plant operation.*

Key words: *wireless sensor networks, power transformers, power plants, management, on-line monitoring, remote control*

1. INTRODUCTION

Global processes of liberalization and deregulation of energy sector have established new technical and technology requirements to the research and development centers all over the world. Imperative requirements are increase of energy efficiency, reliability and availability of energy resources. In the field of testing and diagnostics individual measurements are replaced by integrated models. Timely planned maintenance is replaced by condition based maintenance in respect to the risk assessment using information technologies (databases, intranet, Internet). Requirements of the modern energy market are integrations of several scientific disciplines and technologies: energetic, electronics, informatics, metrology, standardization, management.

Significant savings could be reached by prevention of malfunctions and breakdowns by introduction of on-line diagnostics and condition based maintenance strategy. On-line monitoring gives timely information about process and helps for further decisions about

Received April 10, 2016; received in revised form May 30, 2016
Corresponding author: Aleksandar Nikolić
Electrical Engineering Institute Nikola Tesla, University of Belgrade, 8a Koste Glavinića Serbia
(E-mail: anikolic@ieent.org)

process operation [1]. This type of diagnostics became very important in large power plants and its important equipment, especially high power transformers [2].

Generator power transformers are the largest units in power plants, since their capacity could be even 1400MVA. Nowadays, two approaches for thermal management of such transformers are used. Expensive solution is based on optical sensors mounted in transformer windings during manufacturing or repairing process. Other solution relay on mathematical model of transformer and uses calculation of the highest temperature in transformer (e.g. the *hot-spot* temperature), measuring only transformer top-oil temperature and load current [3].

Solution presented in this paper is based on calculation of the hot-spot temperature using measured transformer oil on the top of housing, ambient temperature and load current. Real-time calculation of the hot-spot temperature and transformer cooling control is implemented in industrial type programmable controller. Temperature sensors are industrial Pt100 mounted on the pipes where transformer oil is circulating. Since the system also controls transformer cooling, it is wise to put one sensor at the input of cooling device and the other on the output. In that case, besides cooling control, more information about operation of cooling device could be obtained, like malfunction of fan if temperatures on the input and output are near the same value.

Studies show that up to 90% of actionable process and environmental data remains uncollected. Wired monitoring systems are expensive and unrealistic in challenging physical environments, and manual monitoring has proven simply to be cost-prohibitive [4]. During analysis prior to implementation of one such a system in one power plant, it was found that cabling would be very difficult and expensive and could yield to a very complicated and unsuitable system. In that case, research about application of some wireless based solution is performed. The reliability of wireless networks is set by the quality of the radio link between the central access point and each endpoint [4]. As a simplest and most reliable solution, a wireless sensor network based system is proposed and results of its implementation and performance in real conditions are presented in the paper.

2. Temperature Monitoring of Power Transformers

Dominantly, in transformer heat is spread by convection. Determination of temperature distribution in transformer, as a dominant loading factor, is very complicated task. Temperature is different in all functional parts of transformer (winding, core, tank and oil) and its changes per volume of each part. The maximum temperature occurring in any part of the winding insulation system is called the "hot-spot temperature“. This parameter represents the thermal limitation of loading of the transformer.

For on-line temperature monitoring it is suitable to calculate hot-spot temperature using differential equation with load factor and ambient temperature as a time variables [1]. Real-time algorithm is developed using concept with differential equation from IEC 60076-7 standard, since it is suitable for on-line monitoring [3]. Load factor and ambient temperature are time dependent variables and there is no limit regarding loading profile. If temperature rises are calculated using exponential functions, expression for hot-spot temperature is given in the equation (1):

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left(\Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R} \right)^X - \Delta\theta_{oi} \right) \cdot f_1(t) + \Delta\theta_{hi} + (Hg_r \cdot K^Y - \Delta\theta_{hi}) \cdot f_2(t) \qquad (1)$$

where $\Delta\theta_{hi}$ is hot spot temperature at the start, $f_1(t)$ is function of top oil temperature increase and $f_2(t)$ is function of hot spot temperature increase depend on top oil temperature.

2.1. Importance of power transformer on-line monitoring

As mentioned in introduction, power transformers in power plants, esp. generator power transformers are one of the most important units in energy power system. Maintenance of these transformers is complicated and expensive and nowadays it should be wait more than 2-3 years for production of new generator transformer.

Monitoring and supervising systems of these transformers are very useful and necessary in order to improve efficiency, reliability and reduces risk and costs of unexpected failure [2]. Monitoring of transformer run during exploitation period could give accurate failure analyses while extending life of assets. Actual conditions drive maintenance and repair and give possibility for estimating additional operational costs. Saving relevant data for further analysis and creating historical data is a merit for improving on-line diagnostics and creating decision making expert systems.

2.2. On-line diagnostics models

The analysis of the failure modes of the various components leads to a review of the inspection and maintenance procedures of power transformers. On-line diagnostic condition assessment addressing common failure modes:

- Multiple sensors,
- Multiple on-line models,
- All parameters are recorded automatically and continuously,
- Trend and limit alarms.

On-line models are focused on the main tank of transformer [3]. These models rely on various sensors installed on the transformer and in the substation, combined with other manually entered parameters. This data is then fed into industry standard and accepted models, which calculate the various outputs.

2.2.1. Load current model

Load current model accept on its input measurements of winding current(s) and on its output it provide trending and alarms of particular load current (Fig. 1).

2.2.2. Winding temperature model

Winding temperature model accept on its inputs top-oil and ambient temperature measurements and measurement of two or three winding currents. Additionally, some fixed parameters should be entered manually as an input of model: rated hot-spot temperature (HSE) rise, rated load current and winding characteristics. On its output it provides trending and alarms of hot-spot temperature for each transformer winding (Fig. 2).

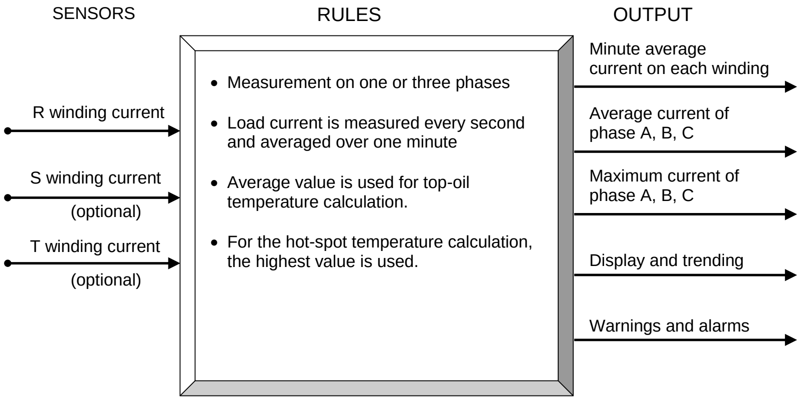

Fig. 1 Load current model

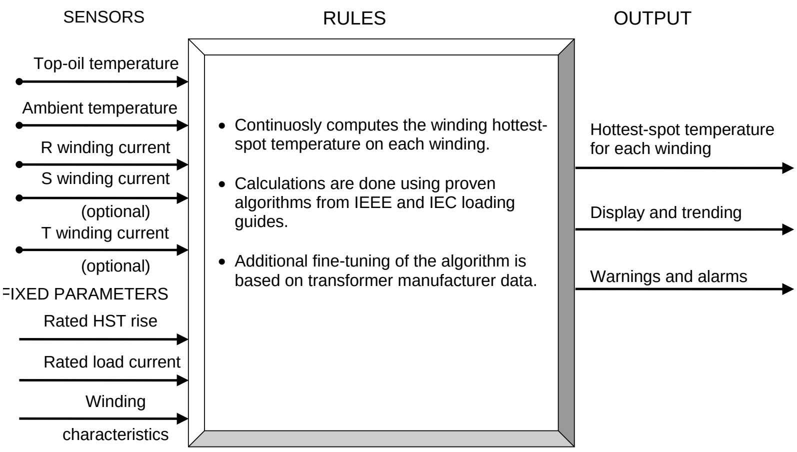

Fig. 2 Winding temperature model

2.2.3. Cooling control model

Cooling control model accept on its inputs top-oil temperature measurement and measurement of two or three winding currents. Optionally, signal about cooling stage status could be also introduced. Additionally, some fixed parameters should be entered manually as an input of model: top-oil temperature set point, hot-spot temperature set point and load current set point. On its output it provides cooling stages ON/OFF control and status, display and trending and status alarms (Fig. 3).

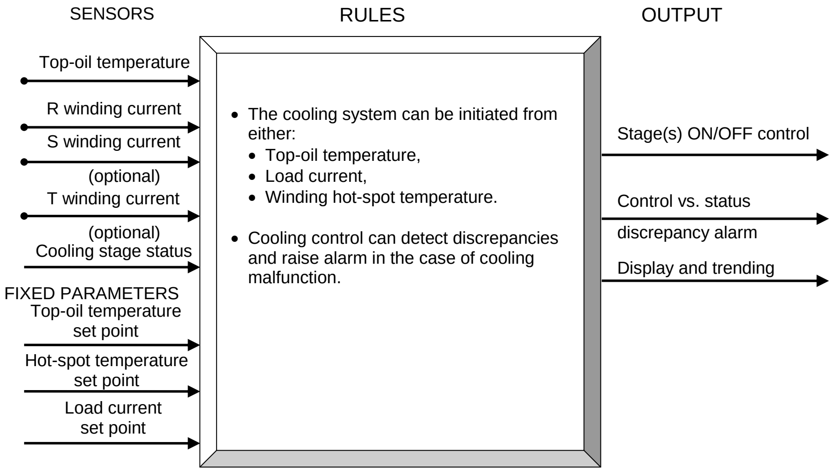

Fig. 3 Cooling control model

2.2.4 . Cooling efficiency model

Cooling efficiency model accept on its inputs top-oil temperature measurement and measurement of two or three winding currents. Optionally, signal about cooling stage status could be also introduced. Additionally, some fixed parameters should be entered manually as an input of model: rated top-oil temperature rise, top-oil time constant, load losses over no-load losses ratio and oil exponent. On its output it provides information about top-oil temperature discrepancy, warning about deficiency of cooling system and gives display and trending information (Fig. 4).

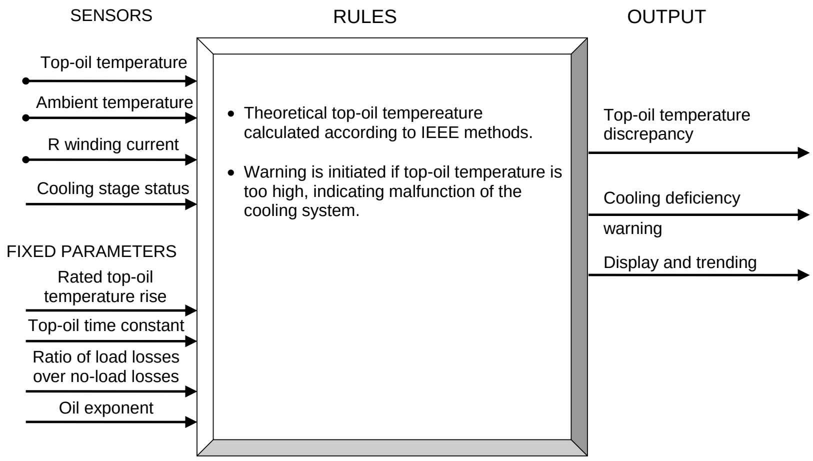

Fig. 4 Cooling efficiency model

3. Industrial Communication Systems

Industrial communication networks are often required to provide tight performance figures in terms of both real time and determinism. This is a consequence of the application fields, such as motion control, factory automation, manufacturing, and networked control systems in which they are typically employed [5].

Until recently, mostly industrial networks were wired based. Several network solutions were defined, from serial communication known as RS-485 and digital industrial automation protocols like HART Communications Protocol (Highway Addressable Remote Transducer Protocol), Fieldbus and PROFIBUS (Process Field Bus). Subsequently, at the end of the 1990s, field networks based on the well-known Ethernet technology started to be introduced. They are characterized by strong performance figures in that they are able to provide high transmission rates (typically up to 100 Mb/s), very limited and predictable transfer times, high determinism, and low jitters. One of the extensions is EtherCAT - Ethernet for Control Automation Technology - an open high performance Ethernet-based fieldbus system.

3.1. Wireless communications in industry

Recently, wireless networks started being considered an interesting solution for communication at the device level as well. Among the first applications was in the wireless control of cranes in warehouses, where proprietary radios achieved flexible control of moving devices. During the past decade, standardized radio technologies like Wireless LAN (IEEE802.11), Wireless HART (IEEE 802.15.4) and Bluetooth technology (IEEE802.15.1) have become the dominating technologies for industrial use. No single wireless technology offers all the features and strengths that fit the various industrial application requirements, so standardized wireless technologies, such as Wireless LAN, Bluetooth and Wireless HART (as well as a number of proprietary technologies) are all used in practice [6].

3.2. Wireless Sensor Networks principle

A wireless sensor network (WSN) is a wireless network consisting of distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations. In addition to one or more sensors, each node in a sensor network is typically equipped with a radio transceiver or other wireless communications device, a small microcontroller, and an energy source, usually a battery. Although battery supplied sensor is one of WSN features, in industrial applications it is wiser to use external, stable DC supply.

Wireless sensor networks (WSNs) have quickly become an area of great interest in terms of research for both industry and academia. Nowadays, the enormous potential of this technology can be easily seen, along with its inherent difficulties. In fact, the Massachusetts Institute of Technology recently classified WSNs as one of the 10 emerging technologies that will change the world [7].

Sensor nodes are connected wirelessly to the gateway in the center that performs data acquisition and analysis [8]. Connecting to a wireless sensor network with other, usually *Ethernet* networks is realized via the communication module with the function of the gateway. At the top of the hierarchy of wireless sensor networks (where it is necessary to realize a gateway functions) is possible to use the communication module with programmable controller and memory to perform the complete processing of data collected from the sensor nodes and possibly control and management [9]. A simple example of data acquisition system based on WSN is shown in Fig. 5.

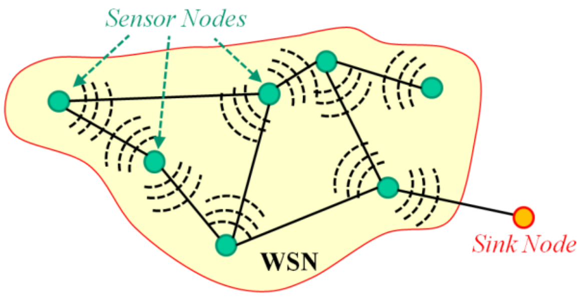

Fig. 5 Example of data acquisition system with wireless data transfer based on WSN

Number of sensor nodes in WSN network could be additionally increased if some of sensor modules are configured as a mesh router. In that case, besides of data transfer from sensors directly connected to the module, it also performs data transfer from some other sensor module in its proximity. WSN node in that case performs functions of data packet routing from their path from the source to the destination [10], as shown in Fig. 5. This shows a way for easily expansion of existing WSN network, both in functional and in space covering aspect [10], [11].

4. Realization of WSN Based Monitoring System

Proposed data acquisition and control system for temperature monitoring of six power transformers and control of transformer cooling of two generator power transformers is based on wireless sensor network. According to the available literature, there is only one similar application in nuclear power plant in USA [12], and few applications in power plants in China [13], [14].

Measuring points in this system are mostly located on the each transformer, with maximum distance less than 50m for each transformer. Distance from transformers to the control room is in the range from 120m to 200m. In that case, developing sensor network with communication links such as GPRS/GSM are not viable because the consumer pays the monthly charges for connectivity.

Finally, a wireless sensor network is defined using ZigBee communication between nodes at transformer and receiver in control room. The lower power ZigBee communication protocol is based on the IEEE 802.15.4 standard and uses the free 2.4GHz ISM band [10]. This makes it viable to read a large number of nodes and justifies implementation and operation costs compared to its benefits.

The IEEE 802.15.4 standard defines two layers, the MAC and the physical layer (PHY) and uses the three license-free frequency bands. These license-free bands have a total of 27 channels divided into 16 channels at 2.4GHz with data rates of 250 kbps, 10 channels at 902 to 928MHz with data rates of 40 kbps, and one channel at 868 to 870MHz with a data rate of 20 kbps. However, only the 2.4-GHz band operates worldwide; the others are regional bands. The 868–870-MHz band operates in Europe, while the 902–928–MHz band operates in North America, Australia, and other countries [7].

For proposed system in thermal power plant chosen WSN sensors are industrial type which already operates on 2.4GHz band, since it is globally available and license free. The reason is not based on the spectral content, although according to the recommendation ITU-R P. 372 industrial noise of any type disappears at 900MHz [15]. Usually in thermal power plant and its surrounding there are no present large number of systems that operates in 2.4GHz frequency band and that could cause interference and endanger installed WSN stability. The other fact is that 2.4GHz ISM has the highest throughput data rate of 250kbps (over 40kbps at 915MHz and 20kbps at 868MHz) and it supports 16 channels (10 at 915MHz and only 1 at 868MHz). These WSN devices are designed to monitor assets or environments in outdoor or harsh settings and hard-to-reach places. It could operate in industrial temperature range (-40°C to 70°C) which have proved also in the case of proposed system. Finally, a variety of international safety, electromagnetic compatibility, and environmental certifications and ratings are available for these devices.

Finally, selected equipment according to IEEE 802.15.4 standard provide development of independent system that do not require significant investment in infrastructure and monthly payments in the case of mobile network based system.

Although sensors in WSN network could be battery supplied and operate several months using standard AA batteries, in the presented system WSN nodes and gateways are supplied from external 24VDC using industrial grade supplies with isolated input/output. Line voltage for these supplies is taken from plant's secured (uninterrupted) supply. Batteries were used to supply nodes only during installation, since at that time particular transformer and its whole supply is switched off due to the maintenance procedure.

Sensor network consists of several measuring nodes per transformer. One analog input type node performs transformer current measurement on one of its analog inputs and control of 4 cooling units via digital outputs. Temperature measuring nodes are connected to Pt100 sensors that measures top-oil temperature, input and output temperature of cooling units and ambient temperature. Receivers (one per each transformer) are placed in the plant control room at the point where transformer could be viewed, in order to avoid lower signal reception. One receiver is equipped with microcontroller and memory, so it is used for real-time algorithm deployment. Both receivers communicate with each other and supervising computer mounted in control room via Ethernet. Position of sensor nodes and WSN gateways is shown in Fig. 6 using aerial view of the power plant. Labels on white background denote power transformers, where 5T and 3T are generator transformers, 25T and 23T are their corresponding self-consumption transformers, respectively, while 1T and 2T are common group transformers. Locations of WSN nodes are marked with yellow circles, while locations of WSN gateways are marked with yellow squares.

Application that runs on supervising PC communicate with receivers via Modbus TCP/IP protocol, display all needed data for operators and store values in MySQL database. In order to provide remote supervision and application modifications, whole system is connected to the Internet via power plant LAN.

In Fig. 7 a part of the realized system is shown for 100MVA generator transformer. Photo is taken from the control room where main receiver with real-time application is mounted. On the right side of Fig. 7 open industrial enclosure in IP65 protection is shown. Installed equipment in enclosure is designated as follows: WSN nodes – 1, WSN antennas – 2, isolated power supply 24VDC – 3, measurement transmitter for translating mA signals into mV – 4, relays for switching fans and oil pumps and reading switching status – 5, 230VAC socket for supply instruments and tools during maintenance – 6.

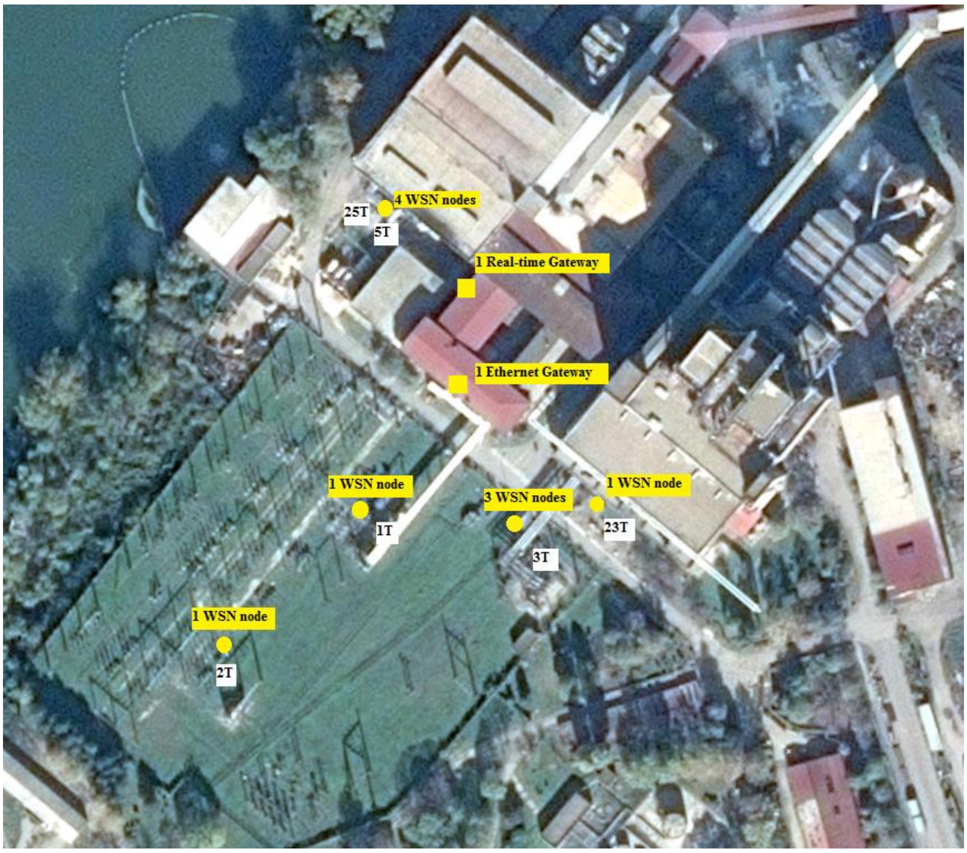

Fig. 6 Disposition of WSN nodes and gateways in thermal power plant

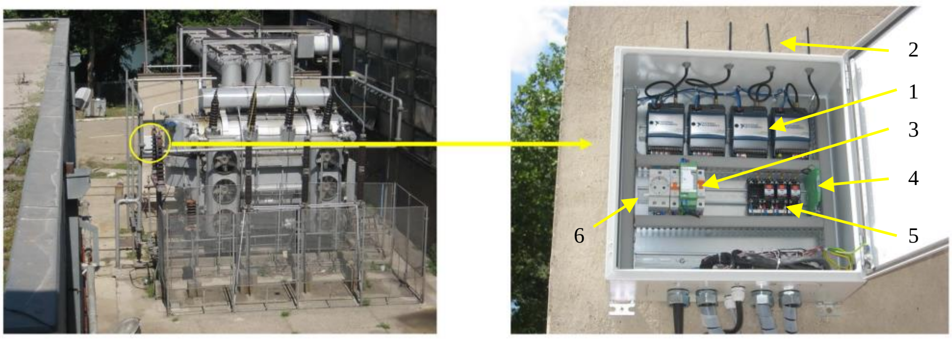

Fig. 7 Industrial WSN based generator power transformer thermal management system

5. Experimental Verifications

During analysis of correct signal reception from nodes to receiver, it is found that several precautions should be done in the complex industrial environments such as thermal power plant.

Each node should be placed in such a way that it could be viewed from the place where receiver is mounted. This is important to avoid signal breakdown at some barriers.

Due to the fact that there are another equipment including large cooling units around transformer, it is better to put all measurement nodes for one power transformer and its auxiliary consumption transformer in a single enclosure, as shown in Fig. 7.

For auxiliary transformers, signals are just added to the existing WSN nodes in the case of transformer 25T and its main 5T. But, for other transformer 23T situation is slightly different, due to the fact that transformer 23T is not placed just behind its main transformer 3T, like 25T and 5T. Transformer 23T is located on the other side of the main road in power plant than 3T. In that case, additional WSN node is used for 23T. Since that node is not viewable completely clear from the control room building, some modifications in WSN network is made. In that case, one of WSN nodes used for transformer 3T (mounted in enclosure near 3T) that is closer to transformer 23T is reconfigured as mesh router. This WSN node, clearly "seen" by mesh router node that resends both its measured data and data obtained from WSN node near transformer 23T.

WSN modules work with a constant output power of the transmitter 10 dBm (10 mW), the receiver sensitivity is -102 dBm. Operation of wireless sensor networks is analyzed by monitoring the change in signal level at the receiver input on each of WSN modules over a longer period of time (one segment results are shown in Fig. 8). The observed dynamics of the signal is in the range of 9 dB to 45 dB, depending on the relative positions of WSN module that provides communication. Wireless sensor network realized in outdoor conditions (outside buildings) in the complex propagation environment of thermal power plant TE Kostolac A. This thermal power plant consists of several buildings representing good reflective surface as the entrance to the recipient causes the existence of a large number of reflected components (besides direct waves). This results in great instability of signal level at the entrances of their receivers (Fig. 8).

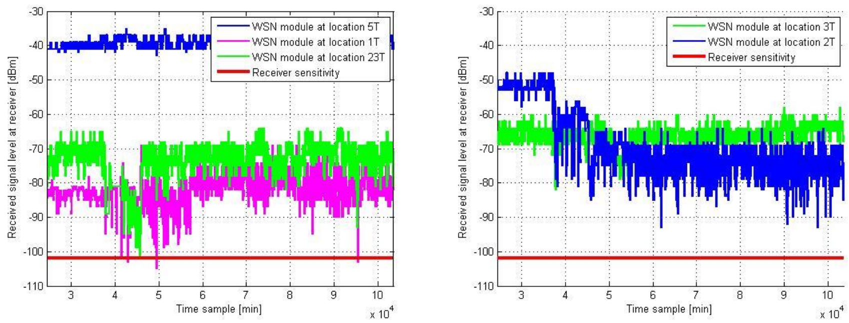

Fig. 8 Signal level change at the inputs of WSN module receivers sampled on 1min

After testing, final places for both WSN nodes at transformers and receivers (gateways) are found. The main criterion is to keep signal level (link quality) over 30%. This assures stable work of whole system during various influences, like disturbances, power disruptions, different weather conditions, etc. Although it is not necessary for a node to be viewed by gateway, for stable work in such an environment we have proved by testing that it is better to provide optical visibility between them, even on the short distances (lower than 100m).

Existing wireless networks should be clearly defined and separated, especially WLANs since their signals have larger level than those in ZigBee networks. In that case, some measurements should be made before to find the most suitable communication channel for ZigBee communication.

The proposed system is developed and is for almost one year under testing in one thermal power plant. It has passed all tests without communication lost or other malfunctions under different plant operation regimes and ambient conditions. It should be noted that during first installations in summer it was over 40°C, while in the winter it was below than -25°C. In both cases, system has worked without any stop. That is confirmed through values stored in SQL database saved on a local hard disk in PC computer mounted the control room.

Results of proper WSN transformer thermal monitoring system are taken through installed application on the panel PC computer in thermal power plant control room. Application receives every ten second updates from real-time gateway and store data into the SQL database. The main screen of the application for data acquisition, which are clearly separated parts that relate to a particular transformer (5T, 25T, 3T, 23T, 1T and 2T), shown in Fig 9. In order to explain meanings of some part of the screen, arrows are pointed characteristic values in the case of transformer 5T: 1 – load current, 2 – top oil temperature, 3 – temperature at the entrance and exit of the cooling group, 4 - calculated hot-spot temperature, 5 – ambient temperature, 6 – cooling group status (green square – group is activated, gray square – group is deactivated).

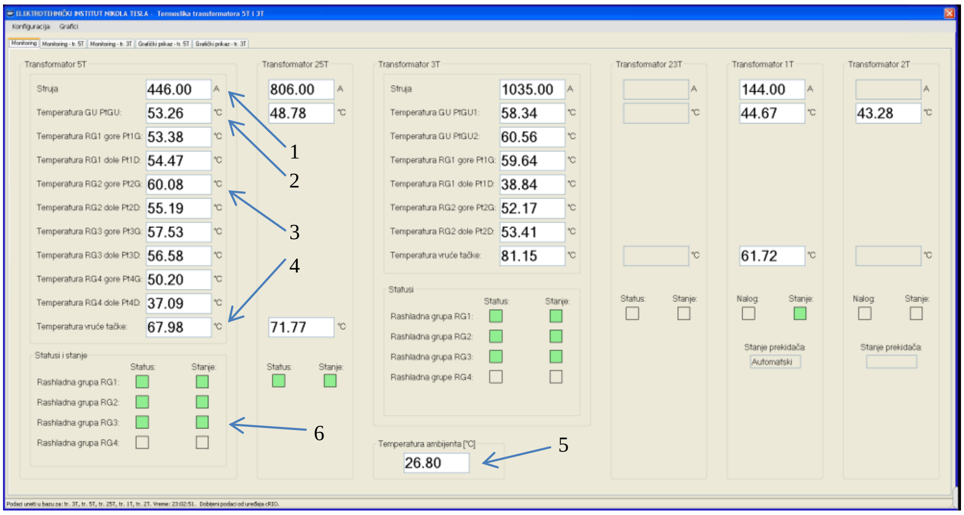

Fig. 9 Signal level change at the inputs of WSN module receivers sampled on 1min

From the Fig. 9 it could be seen that all fields for transformer 23T are grayed. That was due to the fact that transformer 23T was in maintenance, out of operation, when screen was captured from application.

Further merit of proposed system is that application is reachable from outside of the plant through Internet via protected VPN channel. In that case system could be monitored remotely and finally application could be even updated and replaced without necessity to visit the plant. That significantly simplifies system maintenance and reduces additional costs [16].

6. Conclusions

Industrial wireless sensor network system for thermal management of high power transformers is presented in the paper. The importance of implemented on-line temperature monitoring system can be seen in a completely new solution based on wireless sensor networks. This is a unique solution that has been developed due to some potential problems with the installation of cables required for the same purpose. Prior to installation and during the operation of the system, a detailed analysis of the signal quality was carried out on all your wireless connections in a network individually (i.e., for each pair of sensor nodes). After the third upgrade of the system, operation of the wireless sensor network can be remotely monitored and since data about signal quality is recorded in a database on a computer in the control room.

Low consumption WSN modules can work for several months without changing batteries (standard AA type), allows the system to have an additional level of protection in case of failure of the auxiliary power supply in the plant. Also, the system allows easy upgrades by deploying and configuring new WSN Module.

Remote control via the Internet added flexibility to the entire system, allowing the time needed for analysis and testing of transformers significantly shortened. Also remote changes on the software are possible, which for security reasons is performed with the communication and cooperation with operators in the plant. Since in the cases of accidents in power plants efficiency of decision and realization is priority, it is clear what the significance of the realized system is.

Results obtained from the real industrial plant confirm the proposed wireless network configuration, even during very high and very low ambient temperatures.

Acknowledgement: *Results presented in the paper are part of an innovation project "Possibilities for Wireless Sensor Networks Application in Smart Grid Power Systems", granted by Serbian Ministry of education, science and technological development, no. 451-03-2802/2013-16/79, 2014.*

References

[1] B. Sparling, "Transformer monitoring and diagnostics", in Proceedings of the IEEE Power Engineering Society 1999 Winter Meeting, 31 Jan-4 Feb 1999.
[2] B. Flynn, "Case Studies regarding the integration of monitoring & diagnostic equipment on aging transformers with communications for SCADA and maintenance", in Proceedings of the DistribuTECH 2008 Conference and Exhibition, Tampa FL, USA, January 22-24, 2008.
[3] J. Li, T. Jiang, S. Grzybowski, "Hot spot temperature models based on top-oil temperature for oil immersed transformers", in Proceedings of the IEEE Conference on Electrical Insulation and Dielectric Phenomena, 2009. CEIDP '09, 18-21 October 2009, pp. 55.
[4] D. Laurence, "Wireless Sensor Networks", *AWE International*, Issue 15, June 2008.
[5] L. Seno, F. Tramarin, S. Vitturi, "Performance of Industrial Communication Systems", *IEEE Industrial Electronics Magazine*, pp. 27-37, June 2012.

[6] M. Anderson, "A look at wireless technologies for industrial applications", *Industrial Ethernet Book*, Issue 71, pp. 8-13, 2012.

[7] A.-B. Garcı´a-Hernando et al., *Problem Solving for Wireless Sensor Networks*, Springer-Verlag London Limited, 2008.

[8] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, "Wireless sensor networks: a survey", *Computer Networks*, vol. 38, no. 4, 2002, pp. 393–422.

[9] L. Doherty, K.S.J. Pister, L. El Ghaoui, "Convex position estimation in wireless sensor networks", in Proceedings of the INFOCOM 2001, Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies, Anchorage, USA, 2001, pp. 1655 – 1663.

[10] J. N. Al-Karaki, A. E. Kamal, "Routing techniques in wireless sensor networks: a survey", *IEEE Transactions on Wireless Communication*, vol. 11, Issue 6, pp. 6-28, 2004.

[11] K. Holger, A. Willing, *Protocols and Architectures for Wireless Sensor Networks*, West Sussex: John Willey and Sons Ltd, UK, 2007.

[12] R. Lin, Z. Wang, Y. Sun, "Wireless sensor networks solutions for real time monitoring of nuclear power plant", in Proceedings of the Fifth World Congress on Intelligent Control and Automation, WCICA 2004, 2004, pp. 3663-3667.

[13] S. Z. Huang, X. Z. Zhao, "Application of Wireless Sensor Networks on Power Plants Monitoring", *Applied Mechanics and Materials*, pp. 762-766, 2013.

[14] T. Li, M. Fei, "Vibration Monitoring of Auxiliaries in Power Plants Based on AR (P) Model Using Wireless Sensor Networks", *Communications in Computer and Information Science*, vol. 98, pp. 213-222, 2010.

[15] International Telecommunication Union, Radio Communication Sector, *Recommendation ITU-R P.372-12, Radio Noise, P Series Radiowave Propagation*, 07/2015.

[16] A. Nikolic, "Remote Supervising and Decision Support for On-Line Monitoring Systems in Power Plants", Plenary lecture, in Proceedings of the 2nd International Conference on Intelligent Control, Modelling and Systems Engineering (ICMS '14), Cambridge, MA, USA, January 29-31, 2014, pp. 14.