DE GRUYTER OPEN

Arch. Min. Sci., Vol. 61 (2016), No 4, p. 907–915

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.1515/amsc-2016-0060

DARIUSZ JASIULEK*, KRZYSZTOF STANKIEWICZ*, MARIUSZ WOSZCZYŃSKI*

INTELLIGENT SELF-POWERED SENSORS IN THE STATE-OF-THE-ART CONTROL SYSTEMS OF MINING MACHINES

INTELIGENTNE SENSORY SAMOZASILAJĄCE W NOWOCZESNYCH SYSTEMACH STEROWANIA MASZYN GÓRNICZYCH

Perspectives of development of control system dedicated for areas threatened by methane and/or coal dust explosion hazard are presented. Development of self-powered sensors, dedicated for operation in wireless network is one of the development directions. Such a solution will complement typical control systems and it can be used in the places, where there is no possibility of using the typical sensors, in close vicinity to the machine – due to lack of wired connection. General concept of the self-powered sensors with use of two methods of power supply – piezoelectric energy harvester and thermoelectric generator, is given. Perspective of using the methods of artificial intelligence in automatic configuration of sensors network is suggested.

Keywords: piezoelectric energy harvesters; coal mining; sensor; energy harvesting, thermoelectric generator, swarm algorithm

W artykule przedstawiono perspektywy rozwoju systemów sterowania dedykowanych do przestrzeni zagrożonych wybuchem metanu i/lub pyłu węglowego. Jednym z kierunków rozwoju tych systemów jest opracowanie systemu czujników samozasilających, dedykowanych do pracy w sieciach bezprzewodowych. Rozwiązanie takie będzie stanowić uzupełnienie typowych układów sterowania, możliwe do zastosowania w miejscach, w których nie istnieje możliwość zainstalowania czujników konwencjonalnych lub w bezpośrednim otoczeniu maszyny, w przypadku braku możliwości połączenia przewodowego. W artykule została przedstawiona ogólna koncepcja sieci czujników samozasilających z uwzględnieniem dwóch metod zasilania – z zastosowaniem piezoelectric energy harvester (odzysk energii z użyciem piezoelektryków) oraz termogeneratorów. Przedstawiona została również perspektywa zastosowania metod sztucznej inteligencji w automatycznej konfiguracji złożonej sieci komunikacyjnej obejmującej przedmiotowe oczujnikowanie.

Słowa kluczowe: odzysk energii z użyciem piezoelektryków, górnictwo, czujnik, pozyskiwanie energii, termogenerator, algorytm roju

* KOMAG INSTITUTE OF MINING TECHNOLOGY, PSZCZYNSKA 37, 44-101 GLIWICE, POLAND. E-mail: djasiulek@komag.eu, kstankiewicz@komag.eu, mwoszczynski@komag.eu

Unauthenticated
Download Date | 1/28/17 3:38 PM

1. Introduction

Development of the systems for monitoring and automation of machines and equipment, including mining machines, requires implementation of new solutions (Bartoszek et al., 2013a, 2013b; Jasiulek & Świder, 2013). In the case of operation in areas threatened by methane and/or coal dust explosion hazard implementation of state-of-the-art technologies is associated with special safety requirements resulting from 2014/34/UE ATEX Directive. Dispersed control systems, based on industrial networks (e.g. CAN bus) become more and more popular (Bartoszek et al., 2013c; Jura et al., 2013). Use of industrial networks is aimed at limiting the number of cables (in practice it is often necessary to combine a network cable and a power cable in one cable). The sensors, which communicate with each other through wireless network, require supply from power cables or from batteries. In the case of devices dedicated to mining machines, the battery supply is troublesome due to technical problems of batteries replacement, their weight and safety requirements.

A concept of the system of self-powered sensors was developed within the work carried out by KOMAG (Jasiulek, 2014; Jasiulek et al., 2012, 2013). The innovativeness of the suggested solution consists in a possibility of using the system in mines, in areas threatened by methane and/or coal dust explosion hazard. According to the Regulation of the Minister of Economy of 22 December 2005 (Journal of Laws No. 263, item 2203) the devices and protective systems intended to be used in areas threatened by explosion hazard require proper anti-explosion protections. For this case, 2014/34/UE ATEX Directive is the legal act obligatory in the entire European Union. General requirements concerning design of electric devices used in areas threatened by explosion hazard are included in PN-EN 60079-0:2009 Standard harmonized with ATEX Directive. Intrinsically safe design is the best method of protection in the case of electronic devices. Intrinsic safety is usually ensured by proper enclosure which collects and limits the electricity in the device (and its wiring), which has a contact with explosive atmosphere, to the level that will not cause ignition in a result of sparkling and warming up. Requirements as regards a type of design are determined in PN-EN 60079-11:2012 Standard.

Taking into account the requirements of regulations, a concept of the system of self-powered sensors, which use piezoelectric energy harvesting and thermoelectric generators as supplying components, was developed. It is planned to use the methods and techniques of artificial intelligence in management of sensors network configuration. In the mining industry artificial intelligence is used especially in diagnostics of wear of sub-assemblies and parts (Prostański & Jonak, 2003) as well as control systems of machines and mechanization systems (Bambor, 2012; Jasiulek et al., 2011). Implementations enabling intelligent adaptation of machines to the changeable operational conditions are known. Future mining of thin seams in conditions of high methane content threatened by bumping hazard and thermal hazard, forces the designers to develop the systems of higher and higher autonomy to limit the role of man mainly to the remote control.

2. Possibility of using self-powered sensors

Basing on KOMAG experience in designing the machines dedicated for the mining industry, the requirements for using the self-powered sensors were analyzed. Needs of designers, manufacturers and users of mining machines were considered. It has been found that in the case

Unauthenticated
Download Date | 1/28/17 3:38 PM

of designing or modernization of mining machines' control systems, there is a problem in laying power and control cables due to lack of room or due to potential risk of cable damage during its use. The regulations resulting from the ATEX Directive are the other problem associated with modernization of existing control systems. Entering the changes to the existing power and control systems of mining machines is often problematic or even impossible. Use of self-powered sensors will enable incorporating additional options associated with monitoring of machines operational parameters without necessity of intervention in the existing power and control systems and without necessity of laying additional cables. Applications of self-powered sensors result directly from availability of energy source. In this paper, we have focused on energy from electric vibrations or energy from temperature difference.

A. Energy of mechanical vibrations

During analysis of the possibility of using the self-powered sensors powered by energy from mechanical vibration (Michalczyk, 2012), it was found that they could be used especially in mobile machines or in the machines operating in longwall mining system (Dolipski et al., 2012) or in roadheading system.

The following parameters, which could be measured by the target sensors system, were selected:

- temperature of the selected design nodes, at any place with a possibility of changing the sensor position during machine operation,
- pressure in hydraulic system of the machine,
- vibrations (vibrodiagnostics),
- stress of flight-bar conveyor's chain – sensor converting the mechanical energy is installed in a specially designed measuring cell equipped with piezoelectric element.

B. Energy from temperature difference

Confined space of operation of mining machines as well as high power of the machines drives cause that the components of machines operating in longwall mining systems or in road-heading systems significantly warm up. Maximal temperature measured on the machine surface should not exceed 150^{o} C. There is a risk that in the case of drive failure or excessive wear of the machine the temperature will be exceeded. The suggested concept of the self-powered sensor is based on thermal energy. Such a sensor will enable taking temperature measurements in the selected design nodes with a possibility easy change of its position.

3. Sensors powered by vibration energy

Piezoelectric sensors use the phenomenon of generation of electric charge on the surface of piezoelectric material under mechanical stress. According to the PN-EN 60079-11:2012 Standard it is necessary to test mechanically the machines having these sensors, if they are planned to be used in areas threatened by methane and/or coal dust explosion hazard:

"Measure both the capacitance of the device and also the voltage appearing across it when any part of the intrinsically safe apparatus which is accessible in service is impact tested in ac-

Unauthenticated
Download Date | 1/28/17 3:38 PM

cordance with the "high" column of Tests for resistance to impact table in IEC 60079-0 carried out at (20 ± 10) °C. (...) For the value of voltage, the higher figure of the two tests on the same sample shall be used. (...) The maximum energy stored by the capacitance of the crystal at the maximum measured voltage shall not exceed the following: for ***Group I*** *apparatus: 1 500 μJ.*" (EN 60079-11:2012 item 10.7).

If the maximal output energy of the given machine exceeds the value given in item 10.7 of EN 60079-11:2012 Standard, it is suggested to install the piezoelectric element in a hermetic enclosure, to cover it with a filling compound and then to place it in a special enclosure resistant to mechanical stress. Such prepared device should meet the requirements given in PN-EN 60079-11:2012 Standard put to the intrinsically devices of "ia" protection level (continuous operation in a presence of methane).

A. Suggested structure of the sensor

After initial analyses, it was concluded that the wireless sensor would be composed of four following main modules:

- measuring element – depending on a type of sensor it could be for instance piezoelectric element for measuring vibrations, thermocouple for measuring temperature or element for pressure measurements,
- processor – physical parameter measured by the sensor is transferred by the processor from analogous form into digital form and it is then sent in a proper format to radio transmission system. Besides, the processor will have logics which would enable self organization of radio communication,
- data radio transmission system – after review of available systems it was found that ZigBee is the best standard for radio data transmission to be used in a discussed case,
- supply – in typical wireless sensors the battery power supply system is used. The alternative power source for all sensor subassemblies will be suggested.

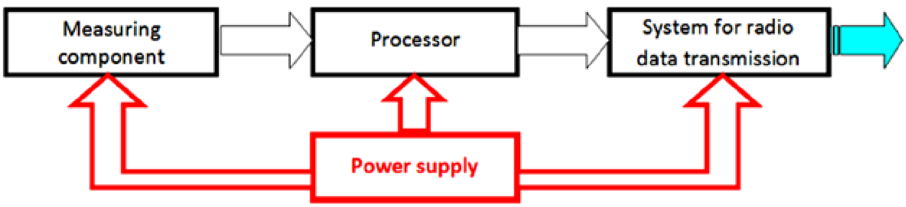

Fig. 1. Diagram of self powered sensor structure (Jura et al., 2012)

4. Sensors with thermoelectric power supply

Industrial manufacturing processes (including the mining industry) generate large amount of waste thermal energy. Due to this, work on development of thermoelectric generators of highest possible conversion of thermal energy into electricity, is carried out. Several significant features, such as lack of movable parts, direct conversion of thermal energy into electricity, small

Unauthenticated
Download Date | 1/28/17 3:38 PM

dimensions of thermocouples, manufacture of thermocouples in any shape and possibility of their further development due to continuous tests over new thermoelectric materials, speak for use of this type of generators (Stankiewicz & Woszczyński, 2010).

The tests on thermal energy recuperation technology are carried out in different branches of industry, starting from micro-technology (Dziurdzia & Lichota, 2012; Dziurdzia & Stępien, 2011), through automotive industry (General Motors, BMW, Toyota, Ford (Fairbanks, 2008, 2010)), to heavy industry (Kaibe et al., 2011; Woszczyński, 2013). Technology of thermoelectric generators is also used in production processes generating less thermal energy (Dziurdzia & Lichota, 2012; Dziurdzia & Stępien, 2011; Juszczyk, 2005). Dynamic development of state-of-the-art electronic devices, designed with use of nanotechnology, determines their miniaturization and increase of energy savings, what will lead to decrease of amount of electricity indispensable to power these devices. Wireless communication systems, such as Wi-Fi or Bluetooth, are developed at the same time. Method for power supply is an obstacle in constructing the autonomous systems, which ensure continuous operation. Use of energy from surrounding environment, mainly thermal energy, is the key issue to solve this problem. The above conditions enable using the thermoelectric generators, which require temperature gradient of only ten or so degrees on both thermocouple surfaces to generate small power.

Thermoelectric generators are used to convert thermal energy into electricity, which can be used to supply autonomous devices, e.g. wireless sensors. The principle of operation of thermoelectric generators is based on Seebeck phenomenon. It consists in generation of electromotor force in the circuit consisting of two different materials, contacts of which are in different temperatures (Poprawski & Misiewicz, 2001). Contact voltage arises in a result of diffusion of electrons through the contact surface from one material to another. As the result in the material, which has lower concentration of electrons, there is their excess at the contact surface, and lack on the opposite side of the contact. The difference is higher when the contact temperature is higher, because then the diffusion of electrons through the contact is stronger.

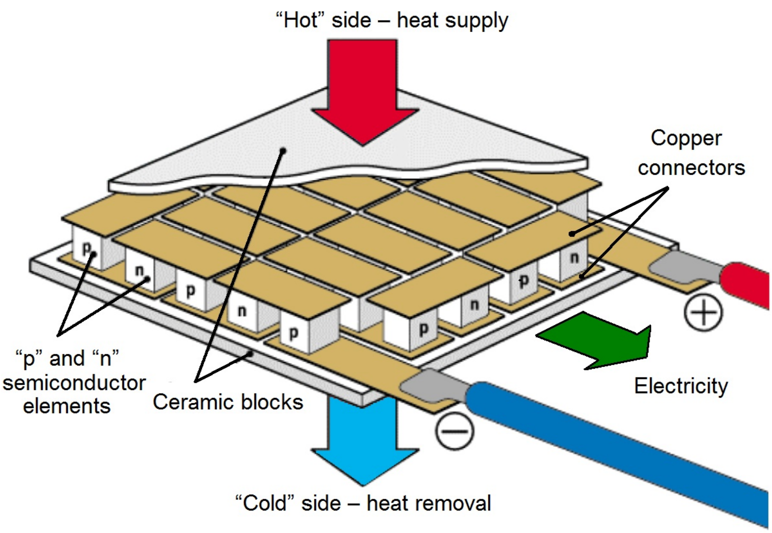

Fig. 2. Design and principle of operation of thermogenerating module (Woszczyński, 2013)

Unauthenticated
Download Date | 1/28/17 3:38 PM

Thermoelectric generators are used to convert thermal energy into electricity, which can be used to power autonomous devices, e.g. wireless sensors. The principle of operation of thermoelectric generators is based on Seebeck phenomenon. It consists in generation of electromotive force in the circuit consisting of two different materials, contacts of which are in different temperatures. Contact voltage appears in a result of diffusion of electrons through the contact surface from one material to another. As the result in the material, which has lower concentration of electrons, there is their excess at the contact surface, and lack on the opposite side of the contact. The difference is higher when the contact temperature is higher, because then the diffusion of electrons through the contact is stronger.

At given temperature a difference on the surfaces of thermoelectric component, there is one point on work characteristics referring to maximal power of thermoelectric module. To use maximally the power, possible to be obtained from generator, the load resistance should be matched in such way to ensure work of the system in this point. This principle is called Maximum Power Point (MPP) electrical tracing (Fig. 2). In the case of any temperature changes, proper control of load resistance is indispensable for MPP tracing.

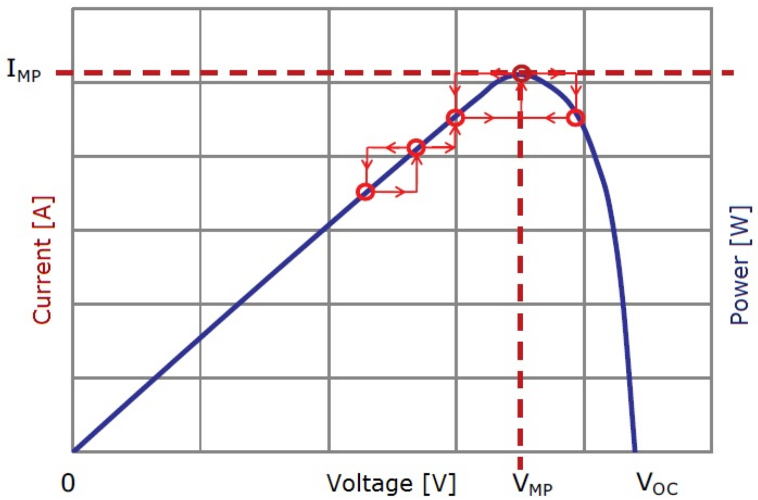

Fig. 3. Tracing o the point of maximal source power (Application note SPV1020)

The concept of autonomous self-powered sensor for monitoring the devices and industrial processes, in which thermal energy is produced, assumes using the following modules:

- power supply – thermoelectric module,
- maximization of energy efficiency – MPPT with the system increasing the voltage and with temporary storage of electricity,
- measurement – e.g. temperature sensor, pressure sensor, etc.,
- control, processing the measured value and data transmission.

Unauthenticated
Download Date | 1/28/17 3:38 PM

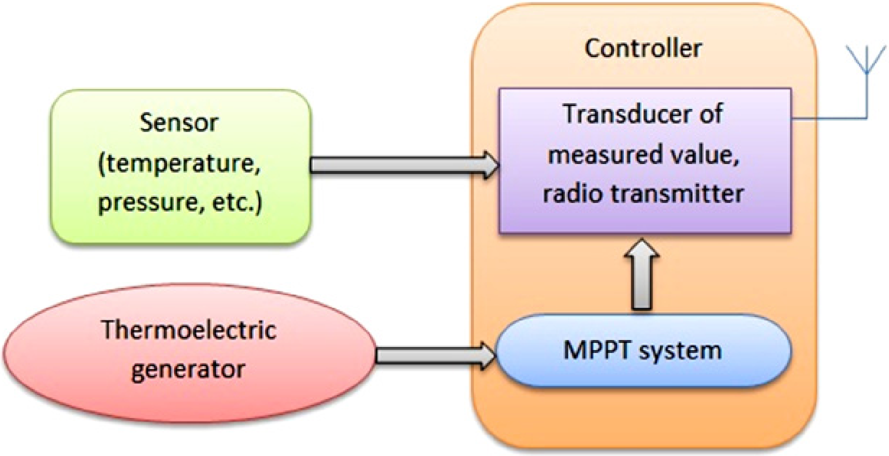

Fig. 4. Block diagram of the sensor with thermoelectric supply

5. Intelligence

A concept of the system of self-powered sensors includes a possibility of any configuration of the network and its change during use. It was decided to use self-organizational algorithms (Stankiewicz, 2011). A concept of the self-organizational communication structure is based on one of artificial intelligence technologies, which is called the swarm intelligence (Arabshahi et al., 2001), which is a direct implementation of phenomena and behaviours observed in the nature among organisms that live in herds. System structures, developed by a man, regardless of the actual implementation, which use this technology, have a significant adaptive capacity and high operational reliability.

In 1987 during the SIGGRAPH Conference the programmer Craig Reynolds in the paper entitled *"Flocks, Herds, and Schools: A Distributed Behavioral Model"* suggested three basic rules of self-organization based on observed groups of animals, i.e.:

- collision avoidance,
- flock centering,
- velocity matching.

Electronic configurations of sensors used in the system will be treated as Monitoring and Transmission Units (MTUs). Transmission priority W_p, which determines efficiency of data transmission to the main transceiver stations, can be assigned to the communication system. This coefficient is based on time of data propagation and number of jumps of transmitted frames with the measuring data. Moreover, the following communication rules should be assigned to each data frame:

1. match its transmission path with data frames from neighbouring MTUs,
2. trying to occupy the place in the path between data frames from MTU, which are in the transmission range,

Unauthenticated
Download Date | 1/28/17 3:38 PM

3. not to compete for primacy in transmission with frames of higher priority,
4. avoid transmission by the units marked as damaged,
5. possibility of leaving the present connection, when the coefficient of transmission priority of MTU group decreases or the main transceiver station was found.

Use of these simple rules causes that MTU group, which makes the transmission connection, creates the structure of reliable transmission path by itself, neglecting the damaged units – just like living creatures do able to separate into two independent groups, when meeting the obstacle, to omit the obstacle and to join again.

6. Summary and conclusions

Selected elements of the concept of self-powered sensors system as well as analysis of possibilities of practical use of the discussed system in mining applications are presented.

The method for self-organization of communication system enables to implement state-of-the-art and efficient monitoring and control technology in underground workings, especially regarding the network of self-powered sensors, equipped with proper electronic system, which can be treated as the elements of measuring swarm. Taking into account possible advantages of using these systems, regarding the increase of work safety and elimination of emergencies as well as their relatively low cost it is necessary to carry out further research work aiming at commercialization of self-powered systems in the mining industry

References

Application note SPV1020

Arabshahi P., Gray A., Kassabalidis I., Das A., Narayanan S., Sharkawi M., El Marks R.J., 2001. *Adaptive routing in wireless communication networks using swarm intelligence*. AIAA 19th Annual Satellite Communications System Conference Toulouse, France.

Bartoszek S., Jagoda J., Jura J., 2013a. *System diagnostyczny ładowarki bocznie wysypującej bazujący na iskrobezpiecznej magistrali CAN. Szybkobieżne Pojazdy Gąsienicowe (32) nr 1*. Ośrodek Badawczo-Rozwojowy Urządzeń Mechanicznych OBRUM sp. z o.o., Gliwice.

Bartoszek S., Jagoda J., Jasiulek D., Jura J., Latos M., Stankiewicz K., 2013b. *System wibrodiagnostyczny maszyn górniczych. KOMTECH 2013, Innowacyjne techniki i technologie dla górnictwa*. Bezpieczeństwo – Efektywność – Niezawodność, Instytut Techniki Górniczej KOMAG, Gliwice, s. 347-363.

Bartoszek S., Jagoda J., Rogala-Rojek J., Jagoda J., Latos M., 2013c. *Zmodernizowany system monitoringu konstrukcji obiektów wielkopowierzchniowych*. Maszyny Górnicze, nr 1, 38-43.

Bombor J., 2012. *Sztuczna inteligencja w kopalni Pniówek! Górnicy niepotrzebni*. Dziennik Zachodni, 31.05.2012.

Dolipski M., Remiorz E., Sobota P., 2012. *Determination of Dynamic Loads of Sprocket Drum Teeth and Seats by Means of a Mathematical Model of the Longwall Conveyor*. Archives of Mining Sciences, Vol. 57, No 4, p. 1101-1119.

Dziurdzia P., Lichota K., 2012. *A Compact Thermoelectric Harvester for Waste Heat Conversion, Elektronika: konstrukcje, technologie, zastosowania*. Wydawnictwo Czasopism i Książek Technicznych SIGMA-NOT, R. 53 nr 1, 30-32.

Dziurdzia P., Stepien J., 2011. *Autonomous Wireless Link Powered with Harvested Heat Energy*. COMCAS 2011, International IEEE Conference on Microwaves, Communications, Antennas and Electronic Systems, Tel Aviv, Israel, November 7-9.

Unauthenticated
Download Date | 1/28/17 3:38 PM

Fairbanks J., 2008. *Thermoelectric applications in vehicles status 2008*. U.S. Department of Energy, Washington, D.C., U.S.A.

Fairbanks J., 2010. *Vehicular Thermoelectrics: the New Green Technology*. 16thDirections in Engine Efficiency and Emissions Research (DEER) Conference, Detroit, Michigan, September 29.

Jasiulek D. et al., 2012. *Alternatywne źródło zasilania czujników stosowanych w górnictwie*. ITG KOMAG, Gliwice (materiały niepublikowane).

Jasiulek D., Stankiewicz K., Jagoda J., 2013. *Możliwości zastosowania czujników samozasilających się przeznaczonych do pracy w podziemiach kopalń*. Mechanizacja i Automatyzacja Górnictwa, nr 8(519), 73-80.

Jasiulek D., 2014. *Propozycje zastosowania czujników samozasilających się w przemyśle wydobywczym*. Przegląd Górniczy, nr 1/2014, 9-15.

Jasiulek D., Świder J., 2013. *Mechatronic systems in mining roadheaders – examples of solutions*. Pomiary Automatyka Robotyka, nr 1/2013, 121-127.

Jasiulek D., Rogala-Rojek J., Stankiewicz K., 2011. *Możliwości zastosowania technik sztucznej inteligencji w układach sterowania i diagnostyki maszyn górniczych. Innowacyjne techniki i technologie dla górnictwa*. Bezpieczeństwo – Efektywność – niezawodność KOMTECH 2011. Monografia, ITG KOMAG, Gliwice, 45-54,

Jura J., Bartoszek S., Jagoda J., Jasiulek D., Stankiewicz K., Krzak Ł., 2013. *System sterowania rozproszonego KOGASTER. KOMTECH 2013, Innowacyjne techniki i technologie dla górnictwa*. Bezpieczeństwo- Efektywność – Niezawodność, Instytut Techniki Górniczej KOMAG, Gliwice, 309-323.

Juszczyk M., 2005. *Zasilanie automatyki rozproszonej*. Control Engineering, 06 2005.

Kaibe H., Kajihara T., Fujimoto S., Makino K., Hachiuma H., 2011. *Recovery of Plant Waste Heat by a Thermoelectric Generating System*. Komatsu Technical Report, Vol. 57, No. 164, 26-30.

Michalczyk J., 2012. *Maximum amplitudes in transient resonance of distributed-parameter systems*. Archives of Mining Sciences, Vol. 57, No 3, 657-665.

Poprawski R., Misiewicz J., 2001. *Zjawiska termoelektryczne – wstęp*. Instytut Fizyki Politechniki Wrocławskiej, Wrocław.

Prostański D., Jonak J., 2003. *Sieci neuronowe w badaniach procesu urabiania skał stożkowymi nożami obrotowymi*. Monografia, Wyd. CMG KOMAG, Gliwice.

Stankiewicz K., Woszczyński M., 2010. *Metody odzyskiwania i przetwarzania energii cieplnej*. Maszyny Górnicze, nr 1, 39-46.

Stankiewicz K., 2011. *Metoda samoorganizacji roju w monitorowaniu i sterowaniu urządzeń w warunkach wyrobisk podziemnych*. Maszyny Górnicze, nr 4, 10-13.

Woszczyński M., 2013. *Sterowanie zasilaniem elektrycznym maszyny górniczej z zastosowaniem układu rekuperacji energii*. Praca doktorska.

Unauthenticated
Download Date | 1/28/17 3:38 PM