**Miroslav GUTTEN** [1], Jozef JURCIK [1], Adam CICHY [2], Jerzy ROJ [2]
[1] DEPARTMENT OF MEASUREMENT AND APPLIED ELECTRICAL ENGINEERING, FACULTY OF ELECTRICAL ENGINEERING, TECHNICAL UNIVERSITY OF ZILINA, Slovakia
[2] INSTITUTE OF MEASUREMENT SCIENCE, ELECTRONICS AND CONTROL, AND APPLIED ELECTRICAL ENGINEERING, FACULTY OF ELECTRICAL ENGINEERING, SILESIAN UNIVERSITY OF TECHNOLOGY, Gliwice, Poland

# Analysis of the gasoline engines electronic injection system

**Ph.D. Miroslav GUTTEN**

Professor at Zilina University, Ph.D. in electrical engineering defended in 2002, habilitation in 2008. His interests are: teaching, e-learning, new teaching methods, diagnostics and measurements of electric devices.

*e-mail: gutten@fel.uniza.sk*

**Ph.D. Adam CICHY**

Received the M.Sc. (1989) and Ph.D. (1998) degrees in electrical engineering from the Silesian University of Technology, Gliwice, Poland. He currently works at Institute of Measurement Science, Electronics and Control, Silesian University of Technology. Member of the IEEE. Main research interests: measurement of impedance components, especially in the VLF band.

*e-mail: adam.cichy@polsl.pl*

**Ing. Jozef JURČÍK**

His interests are focused on: teaching, e-learning, new teaching methods, diagnostics and measurements of electric devices.

*e-mail: jozef.jurcik@fel.uniza.sk*

**Ph.D. Jerzy ROJ**

Received the M.Sc. and Ph.D. degrees in electrical engineering from the Silesian University of Technology, Gliwice, Poland, in 1989 and 1998, respectively. His research interests include intelligent signal processing, improving accuracy of measuring instruments by using a microprocessors and artificial neural networks.

*e-mail: jerzy.roj@polsl.pl*

**Abstract**

The paper presents the electronic fuel injection system research results, which can be used in diagnostic issues. Have been described the construction and operation of a typical fuel injection system and analyzed its electronic part. It has also been proposed method for the detection of the injector malfunction, based on the analysis of differential current characteristic. Have been shown differences in the electrical parameters of the individual fuel injectors, which can be corrected e.g. by suitable self-learning algorithms.

**Keywords**: electronic fuel injector, diagnostics.

## Analiza elektronicznego układu wtryskowego silników benzynowych

**Streszczenie**

W artykule przedstawiono wyniki badań dotyczących elektronicznego układu wtryskowego paliwa silników spalinowych, które mogą mieć zastosowanie w zagadnieniach diagnostycznych. Opisano budowę i zasadę działania typowego układu wtryskowego oraz poddano analizie jego część elektroniczną. Przedstawiono stanowisko pomiarowe umożliwiające m.in. jednoczesne wyznaczanie charakterystyk prądowych oraz napięciowych dla 5 układów wtryskowych. Uzyskane charakterystyki pozwoliły na opracowanie metody wykrywania nieprawidłowości w działaniu układu wtryskowego opartej m.in. na analizie różnicowej charakterystyki prądowej. Prądową charakterystykę odniesienia przyjęto jako średnią z 5 charakterystyk prawidłowo działającego układu wtryskowego. Stwierdzono, że na podstawie różnicy pomiędzy charakterystyką odniesienia a charakterystyką nieprawidłowo działającego układu wtryskowego możliwe jest wykrycie typowych usterek, takich jak: zatrzymanie zaworu iglicowego w położeniu otwarcia, przesuwanie się zaworu iglicowego tylko w początkowym fragmencie jego zakresu ruchomego, czy też efekt spadku ciśnienia podawanego paliwa. Istotnym problemem przy tego rodzaju diagnostyce jest różnica parametrów poszczególnych egzemplarzy elektronicznych układów wtryskowych, nawet w przypadku tego samego producenta określonego modelu. W rezultacie konieczne staje się wyznaczanie prądowych charakterystyk odniesienia indywidualnie dla każdego egzemplarza. Problem ten może być rozwiązany np. na drodze programowej, przy użyciu odpowiednich algorytmów samouczących.

**Słowa kluczowe**: elektroniczny wtryskiwacz paliwa, diagnostyka.

## 1. Introduction

Electronic fuel injector is an important part of the engine gasoline fuel system. The fuel injector is a solenoid valve. Forces which act on the active injector core are caused by friction, spring tension and fuel pressure. Rising current curve is partially different from the curve of an ideal inductor current. The effect which causes a change of permeability is caused by the movement of the needle valve. Injector opening time is visible on the current characteristics and the closing time – on the voltage characteristics. Stopping the movable element of the injector is seen as disturbance on the measured characteristics.

## 2. Principle of the electronic fuel injector operation

Electronic fuel injector is an electromagnetic valve. Its internal structure is shown in the Fig. 1. The basic part of the valve is armature, needle valve, iron core, electromagnetic coil and return spring. Before injection, the needle valve is compressed tightly on the fuel needle valve pedestal by spring and fuel. Electromagnetic force provided by injection coil is greater than spring force: fuel pressure and friction force. When the current flows through coil, then needle valve opens upward, electronic fuel injector sprays once. When in injector coil power is turned off, under spring force effect, needle valve electromagnetic force decreases rapidly. Needle valve starts closing, then an injection process will be finished [1, 2].

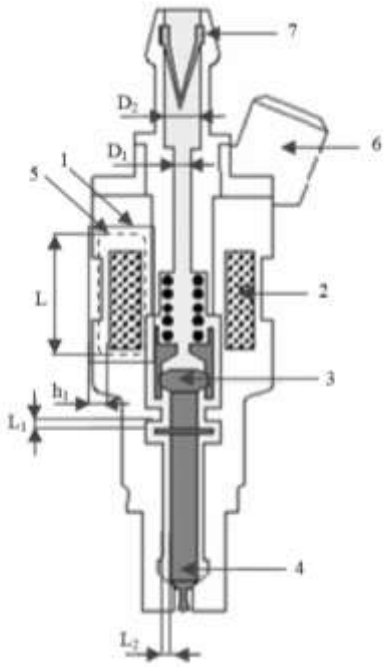


Fig. 1. Construction of an electronic fuel injector [4]: 1-iron core, 2-electromagnetic coil, 3-armature, 4-needle valve, 5-yoke of magnet, 6- electrical connection, 7-filter
Rys. 1. Budowa elektronicznego wtryskiwacza paliwa [4]: 1-stalowy rdzeń, 2- cewka elektromagnetyczna, 3- twornik, 4- zawór iglicowy, 5- jarzmo magnesu, 6- przyłącze elektryczne, 7-filtr

## 3. Basic circuit of electronic fuel injector

Electronic fuel injector control circuit is shown in Fig. 2. When we ignore closing power transistor saturation voltage, the electronic fuel injector coil electrical equivalent circuit can be shown as in the Fig. 3. $R$ and $L$ are equivalent electromagnetic coil resistance and inductance of injector. Circuit voltage equilibrium equation can be written in the form:

$$U_0 = R \cdot i + N \frac{d\Phi_b}{dt} \cdot \tag{1}$$

When there is a coil power failure, the circuit voltage equilibrium equation is:

$$0 = i \cdot (R + R_0) + N \frac{d\Phi_b}{dt}, \tag{2}$$

where $R_0$ is the source resistance.

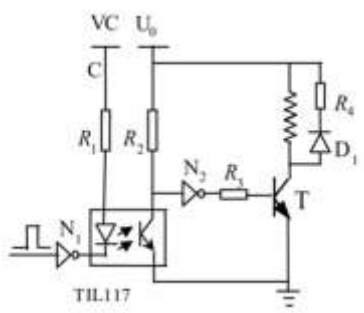


Fig. 2. Injector control circuit [3]
Rys. 2. Układ sterujący wtryskiwacza [3]

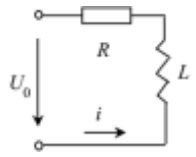


Fig. 3. Equivalent circuit of the injector coil
Rys. 3. Schemat zastępczy cewki wtryskiwacza

## 4. Measuring system for determining the current and voltage characteristics of the fuel injectors

Fig. 4 shows block diagram of the measuring system for gasoline injectors. The main component of the electronic control device is a programmable controller, which is designed to open and close transistors. Injectors are connected to collectors of these transistors. Five button keypad allow setting the transistors opening time. LCD display shows the current mode. In Fig. 5 is shown the view of the measuring station.

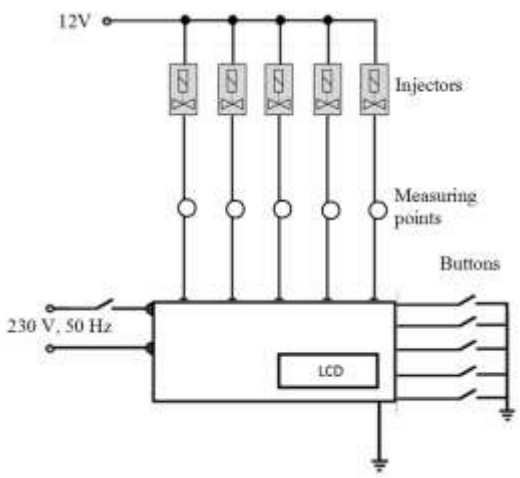


Fig. 4. Block diagram of the measuring system
Rys. 4. Schemat blokowy systemu pomiarowego

Measured current and voltage characteristics show the deviations from the ideal state. Movement of the core, which causes the inductance change, affects on the current and voltage characteristics.

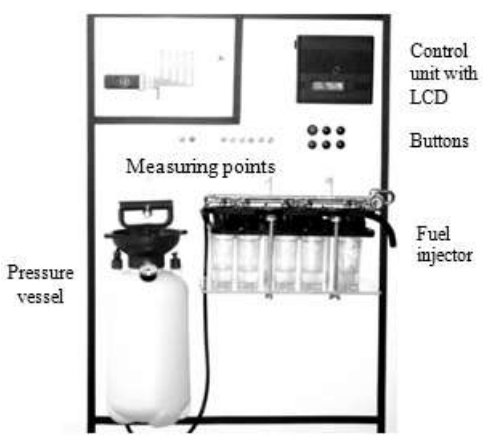


Fig.5. Appearance of the measuring station
Rys.5. Stanowisko pomiarowe

Measurement results shown in Fig. 6 were divided into a few intervals. The interval A is injector inaction, B refers to moving the injector core, C is the injection action with the current increasing, D is injector in operation, E refers to overvoltage caused by the inductance of the injector (moving core injector to initial position), F is fading overvoltage, and G is injector inaction.

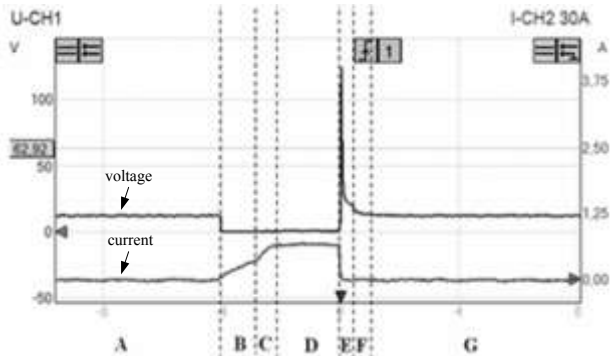


Fig. 6. The fuel injector voltage and current characteristics
Rys. 6. Characterystyki: napięciowa i prądowa wtryskiwacza paliwa

The time required to open the 12-16 ohms injector is about 1.5 ms. This time is depended on the fuel pressure, an injector spring force, an inertial core properties, electromagnetic coil, a core and an injector material. The time required to close the injector is only half of the opening time. Closing of injector is executed by spring and fuel pressure only.

## 5. Analysis of a current characteristics

In Fig. 7a are shown the measured characteristics of the reference current and failure current in the open position.

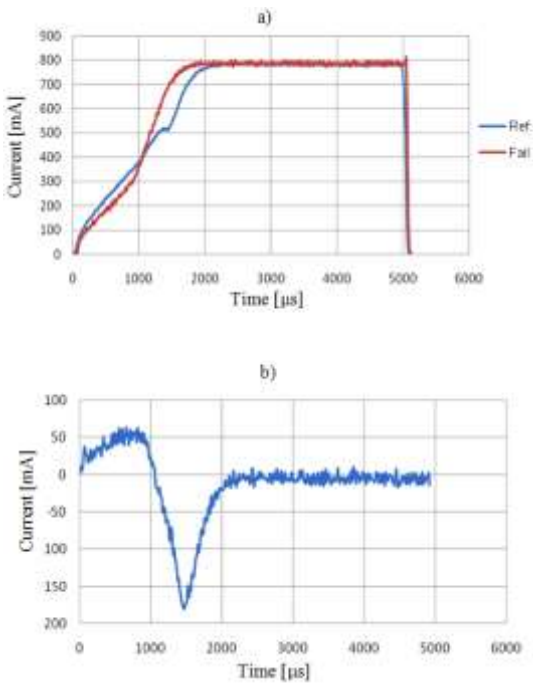


Fig. 7. The waveforms of injector reference current and the current at standstill the needle valve in the open position: a) reference and failure currents, b) their difference
Rys. 7. Przebiegi prądu odniesienia wtryskiwacza oraz prądu przy zawieszeniu zaworu iglicowego w położeniu otwartym: a) prądy: odniesienia i podczas usterki, b) ich różnica

Behaviour of reference current in time was composed from five measurements with the fluid under pressure at 2.5 bar. Sampling value on oscilloscope has been set to 100 kS/s (time between samples is 10 µs). Injection time has been set to 5 ms. The characteristic of the failure current was obtained by stopping the needle valve in the opening position. The difference between the reference and fault currents is shown in Fig. 7b. On this characteristic can be seen two extremes. One of them occurs at 650 µs (for current: 64 mA) and the second - at the 1460 µs (for current: -180 mA).

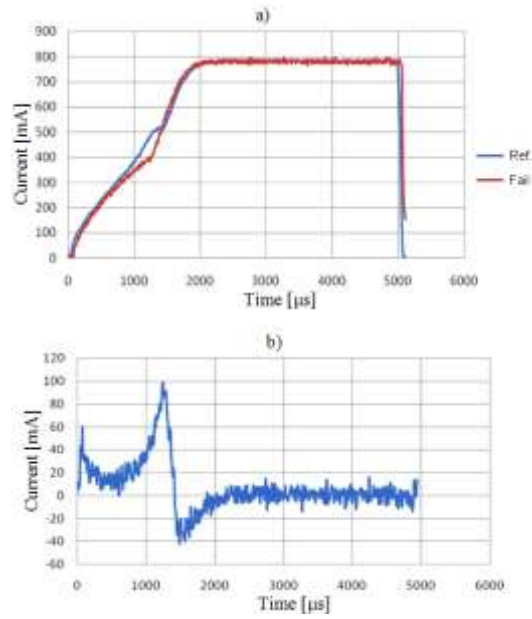


Fig. 8. Injector reference current and the current at partial movement the needle valve: a) reference and failure currents, b) their difference
Rys. 8. Prąd odniesienia wtryskiwacza oraz prąd w przypadku ograniczonego ruchu zaworu iglicowego: a) prądy: odniesienia i podczas usterki, b) ich różnica

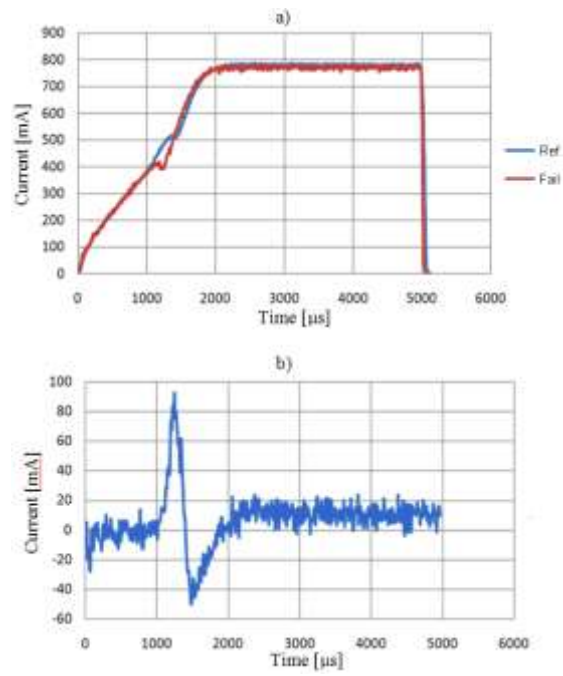


Fig. 9. Injector reference current and current at a fuel zero pressure: a) reference and failure currents, b) their difference
Rys. 9. Prąd odniesienia wtryskiwacza oraz prąd przy zerowym ciśnieniu paliwa a) prądy: odniesienia i podczas usterki, b) ich różnica

Fig. 8 shows the characteristics of current for another, often occurring movement problem of injector valve needle. In this case the needle valve solely moves in the top portions of its moveable sector. The difference between the reference and failure currents again shows the extremes. The first one is marginal for diagnostics of fuel injector. Two others are in 1250 μs (for current: 100 mA) and in 1490 μs (for current:-43 mA).

Reduction of fuel pressure shortens the time necessary to open the fuel injector. This is illustrated by the measurement results shown in Fig. 9. On the differential characteristic, again could be seen two extremes, at 1250 μs (for current: 92,5 mA) and at 1480 μs (for current: -50 mA).

## 6. The injection differences

There are many types of fuel injectors. The difference is mostly in arrays of injection quantity and in a way of injection (e.g. Fig. 10). There are also differences for the fuel injectors of the same type. We obtain differences in the characteristics of four fuel injectors from the same car. Measurement results are visible in Fig. 11 and Fig. 12.

Fig. 10. Differences in injection for different types of injectors
Rys. 10. Różnice wtrysków dla różnych typów wtryskiwaczy

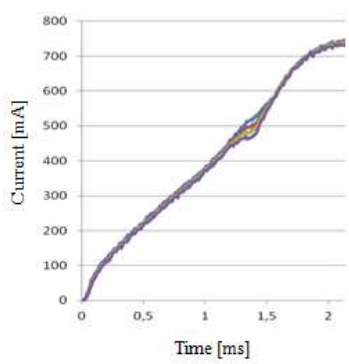


Fig. 11. Differences in current characteristics for the same type of the injectors
Rys. 11. Różnice charakterystyk prądowych dla tego samego typu wtryskiwaczy

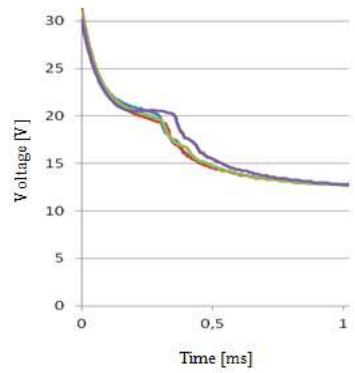


Fig. 12. Differences in voltage characteristics for the same type of the injectors
Rys. 12. Różnice charakterystyk napięciowych dla tego samego typu wtryskiwaczy

## 7. Discussion

In Fig. 13 is visible the influence of fuel pressure changes into current characteristics. The pressure was increased from 0 to 2.6 bar (260 kPa).

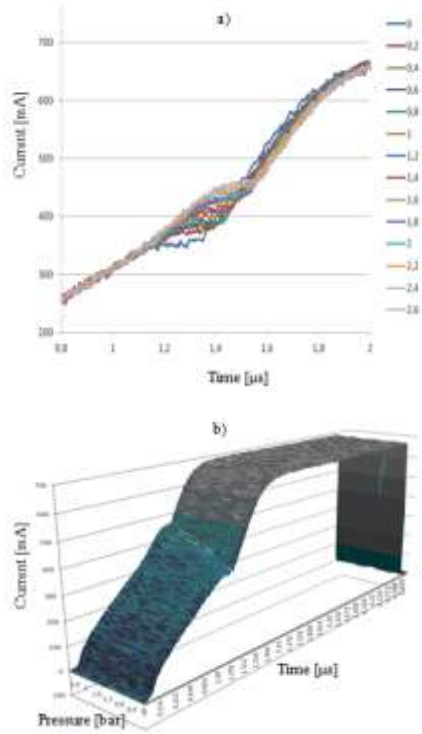


Fig. 13. Effect of changes in fuel pressure into the current characteristics: a) 2d chart, b) 3d chart
Rys. 13. Wpływ zmian ciśnienia paliwa na charakterystyki prądowe: a) wykres 2d, b) wykres 3d

Subtracting the reference signal from the chart shown in Fig. 13b allows to obtain a differential signal, which may be treated as a fault signal or a fault decomposition. Exemplary fault decomposition is illustrated in Fig. 14. As the cause of failure is assumed the fuel pressure drop caused by, for example, inactivity of hot pump, a fuel filters choked, damaged tubes, eventually corrupted regulator pressure.

The time to open the fuel injector is approximately 1.5 ms (Fig.14).

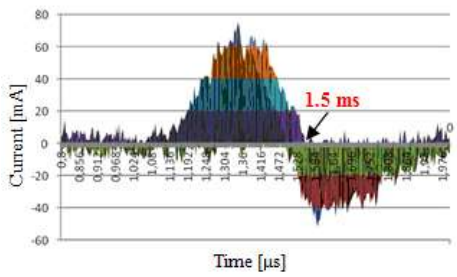


Fig. 14. The currents waveforms during the fuel pressure drop
Rys. 14. Przebiegi prądów podczas spadku ciśnienia paliwa

According to the measuring results, can also be specified failure current at a pressure drop during compression (Fig. 15).

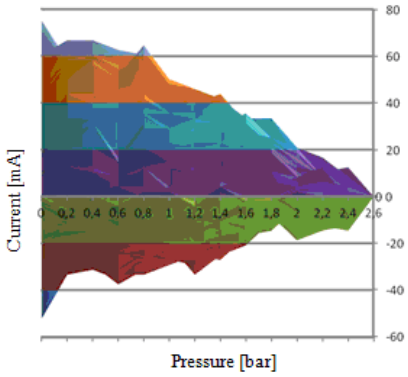


Fig. 15. Change in a current at a fuel pressure drop during the compression
Rys. 15. Zmiana prądu przy spadku ciśnienia paliwa podczas sprężania

## 8. Conclusion

Fig. 16 shows the idealized timing chart of current during fuel injector operation. Have been marked in it some characteristic time moments and the corresponding value of the current, that can be useful for determining the state of the injection system. It is possible to determine the opening time of fuel injector by monitoring the $t_x$ time. This time had influence to pressure ratios of fuel and the injector assembly solution. It is possible to determine a fuel pressure fault by evaluating of these times or determine the damage of the reversible springs of fuel injector. The measurements implemented in the times $t_{m1}$ and $t_{m2}$, allow to obtain the maximum current.

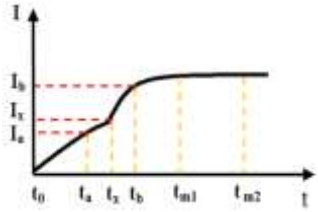


Fig. 16. The current characteristic with marked moments of time in which a current measurement allows to determine the state of the injector system
Rys. 16. Charakterystyka prądowa z zaznaczonymi chwilami czasu, w których pomiar prądu umożliwia ocenę stanu układu wtryskiwacza

The fuel injectors have many differences resulting from the production technology. It causes difference i.a. in the injectors current characteristic. In order to detect the fault state it is needed to use a self-learning process, by the use of an appropriate self-learning algorithm. Such issues will be described in the subsequent paper.

## 9. References

[1] Zhongyi Ma, Yaoyi Qian, Xiumin Yu, etc.: Mathematical Model for the Injection Process of the Electronic Controlled Injectors, In: Transactions of CSICE, Vol.15, No.2, pp.231-236, 1997.
[2] Congbo Yin, Zhendong Zhang, Zhiyuan Liu: Experimental Research and Design for Electronic Control Injector Test about Flow Characteristic, In: Journal of Agricultural Mechanization Research, No.12, pp.194-196, 2007.
[3] Longfa Xiao, Zhendong Zhang, Hui Guo, etc: Research on the Opening and Closing Times of an Electromagnetic Injector, In: Journal of University of Shanghai for Science and Technology. Vol.32, pp.297-301, 2010.
[4] Chen Liangliang, Zhang Zhendong: Study on the measurement of dynamic characteristics for automotive electronic fuel injector, In: 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), Changchun, China, pp. 511-514.
[5] http://performancefuelsystems.com/InjectorCompattibilitywithECUs-TechCorner.htm.
[6] Traistaru, A., Sora, I.: Real time estimation of Li-ion battery resistance used in the automotive industry, In: JEE - Journal of Electrical Engineering, Vol.10, No.4, 2010, ISSN 1582-4594.
[7] Delli Colli, V., Marignetti, F.: Traction Control for a PM Axial-Flux In-Wheel Motor, In: JEE - Journal of Electrical Engineering, Vol.7, No.4, 2007, ISSN 1582-4594.
[8] Kucera, M., Šebok, M.: Electromagnetic compatibility analysis of electric equipments, In: Przegląd Elektrotechniczny = Electrical Review, Vol. 88, No. 9A, 2012, ISSN 0033-2097, pp. 296-299.

*otrzymano / received: 24.08.2014*
*przyjęto do druku / accepted: 01.10.2014* *artykuł recenzowany / revised paper*

**INFORMACJE**

# Informacja redakcji dotycząca artykułów współautorskich

W miesięczniku PAK od numeru 06/2010 w nagłówkach artykułów współautorskich wskazywany jest autor korespondujący (Corresponding Author), tj. ten z którym redakcja prowadzi wszelkie uzgodnienia na etapie przygotowania artykułu do publikacji. Jego nazwisko jest wyróżnione drukiem pogrubionym. Takie oznaczenie nie odnosi się do faktycznego udziału współautora w opracowaniu artykułu. Ponadto w nagłówku artykułu podawane są adresy korespondencyjne wszystkich współautorów.

Wprowadzona procedura wynika z międzynarodowych standardów wydawniczych.

Redakcja