POWER ELECTRONICS AND DRIVES
Vol. 1(36), No. 1, 2016 DOI: 10.5277/PED160101

INDUSTRIAL DRIVE SYSTEMS. CURRENT STATE AND DEVELOPMENT TRENDS*

TERESA ORŁOWSKA-KOWALSKA, MATEUSZ DYBKOWSKI

Wrocław University of Science and Technology, Department of Electrical Machines,
Drives and Measurements, Wybrzeże Wyspiańskiego 27, 50-370, Wrocław, Poland,
e-mail: teresa.orlowska-kowalska@pwr.edu.pl, mateusz.dybkowski@pwr.edu.pl

Abstract: The article presents the current state and development trends of electrical drives, with particular emphasis on modern control structures and safety systems of various types of electrical machines. Special attention was paid to the needs of industrial drive systems and a possibility of practical implementation of complex control algorithms. Development perspectives of electrical drives are discussed from the perspective of new trends in control, power electronics and electrical machines, with consideration given to systems robust to faults of drive system elements.

Keywords: *controlled electrical drive, automation technology, scalar control, vector control, AC/DC rectifiers, fault tolerant control*

1. INTRODUCTION

The market of electrical drives with speed regulation is constantly being developed due to the pursuit to save electrical energy used in industrial installations. There is more and more new industrial equipment with various types of electrical drives. These machines are characterised by particular (specialised) functions for various industry sectors. The needs and requirements faced by electrical drives are different in military or mining industry and still different in the case of precise industry applications.

It has been over 180 years since the first electrical drive was invented, however, a continuous increase in the number of solutions related to the transfer of motion using various types of electrical machines can be observed. Recently published research show an explicit trend common for contemporary drive systems. DC drives, which experienced the peak of their popularity in the 1990's, now are used only in specialised industry sectors. For over twenty years the most popular machines have been induction motors [1], [2]. Their simple construction, reliability, price and ease of con-

---

* Manuscript received: June 23, 2016; accepted: July 2, 2016.

trol are the reason why more than 90% of users declare their use in industrial systems [3], [4]. Another group of machines which currently enjoys great interest in different applications are synchronous motors, especially permanent magnet synchronous motors (PMSM). There is also a considerable interest in solutions using stepper motors and brushless direct current motors (BLDCM) [1]–[4] (Fig. 1).

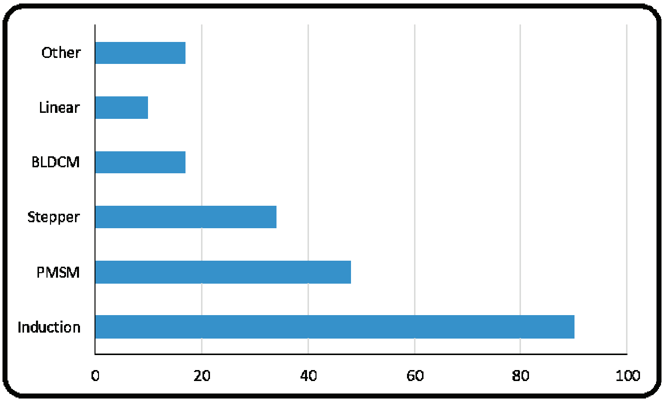

Fig. 1. Motors used in industry [4]

One of the most important aspects of electrical drive systems is their mechanical efficiency and energy efficiency [3]–[5]. Electric motors use about 30–40% of the world power output and about 90% of power used in industry [4]. Hence the pursuance of the improvement of energy efficiency of electrical machines in research and state institutions seems understandable. The role of the European Union in this process is significant as it issued a directive banning electric motors of the lowest efficiency from sale starting from the mid-2011 [4] (in the so called IE1 class).

Current standards IEC 60034-30:2008 and IEC 60034-2-1:2007 indicate the way electric motors are classified. They define the following efficiency classes:

- IE1 – Standard efficiency,
- IE2 – High efficiency,
- IE3 – Premium efficiency,
- IE4 – Super Premium Efficiency.

In practice the introduction of efficiency standards obligates users to choose only these machines which are characterised by increased efficiency. As was mentioned earlier, since June 2011 all motors with output power 0.75–375 kW must fall at least in efficiency class IE2. Since 2015 motors in the power range of 7.5–375 kW must correspond to efficiency class IE3 or IE2 when regulation of rotational speed is used, and in 2017 these regulations will encompass higher power motors [4], [5].

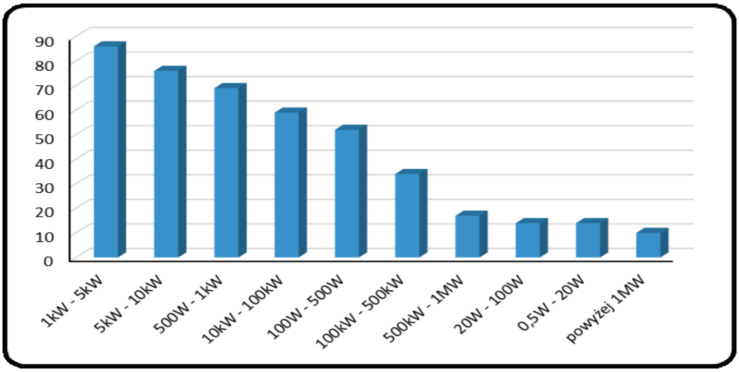

Fig. 2. Power of electric motors used in industry [4]

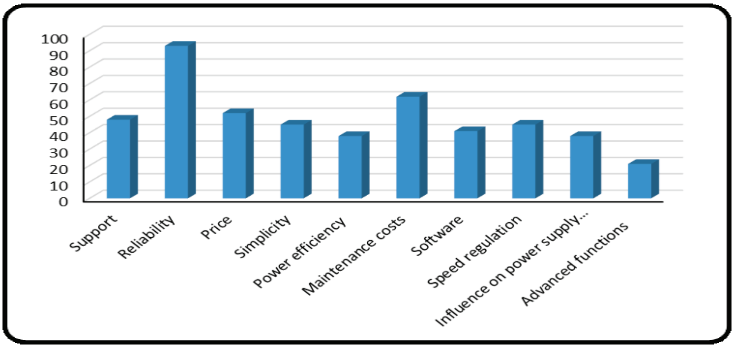

Fig. 3. The most significant characteristics of electrical drives

In practice this means that in the near future most machines used in industry (Fig. 2) will be equipped with a variable frequency drive with a possibility of angular speed regulation even when a technological process does not require this type of control algorithm.

Market analysis clearly shows that the issues of power efficiency and maintenance costs are one of the most important aspects for electric drive users (Fig. 3). Apart from reliability, which naturally is the most significant element, power efficiency and related maintenance costs are an essential factor in choosing a drive system.

The analysis conducted in [3] shows that recently the perception of drive systems has changed. In Fig. 4, a current situation on the market is shown in comparison with recent years (very good, good and poor – describes this market situation). An increasing number of users positively assessed the usefulness and necessity to use variable frequency drives. There is also a growing interest in servo systems allowing for multiaxial positioning and control due to the increasing complexity of technological processes. Simultaneously one can observe a certain decrease in the interest in drive systems with induction motors which dominate in universal, individual and group drives (Fig. 4). As a result, one can state that current development trends are and will be strictly connected with drive energy efficiency, electric power quality and influence on the environment.

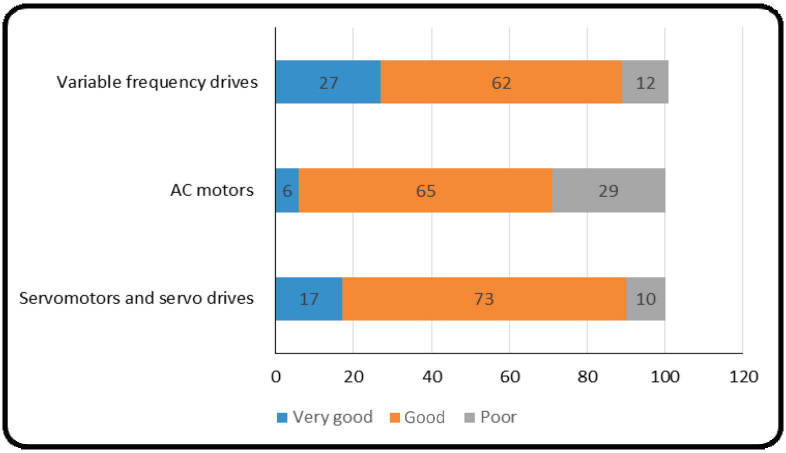

Fig. 4. Current situation on the market of electrical drives [4]

Another problem which is developing alongside the above mentioned one is the issue of safety and robustness to faults of the elements of a drive system. These issues will be briefly discussed in the further part of this work.

The article will not discuss any issues related to communication and programming functions of practically all variable frequency drives. They and their development (grandly named the Fourth Industrial Revolution) currently are the subject of numerous publications [3], [5].

2. MODERN INVERTER DRIVE SYSTEMS WITH AC MOTORS

The idea of drive systems with regulated speed was generated by Harry and Ward-Leonard at the turn of the 19th century. Control was conducted by changing stator voltage using resistors integrated in the circuit. The development of drive systems was very fast and it was possible to distinguish the following periods in it [1]:

- era of electromechanical systems with regulated speed started by Ward-Leonard in 1896,
- era of systems with lamp transformers,
- era of “reformation”, started in 1950 by replacing lamp elements with semiconductor couplers – thyristors (SCR),
- era of “revolution” in regulated electrical drives, started at the beginning of the 1970’s with Blaschke’s idea of Field Oriented Control [1] and next developed

in the mid-1980's by Depenbrock [3] and Takahashi [21] with the idea of the direct torque control,
- era of digitally controlled integrated drives started in the 1990's,
- era of the Fourth Industrial Revolution [5], [6].

The incentive for the rapid development of modern, economic drive systems on the one hand was the development of semiconductor technology and power electronics and on the other hand the introduction of new control and regulation related ideas as well as technical opportunities for their implementation. However, the analysis of the current state and development trends of electrical machines shows that new application areas and natural environment protection requirements lead to a necessity to replace constant speed drives with regulated drives, in which not only speed, but also other state variables are controlled in closed regulation systems [6], [7].

The market of regulated speed drives is developing very fast. Taking into account the constantly decreasing unit price, the number and value of regulated drive systems being sold are predicted to grow in the near future. At the moment AC drives, induction and permanent magnet synchronous motors dominate in new installations of drive systems with high requirements related to the dynamics and/or position regulation. Additionally, the latter ones are used mainly in servo drives while induction drives are treated as universal drives for various industrial applications [1], [4], [5]. Due to the price of permanent magnets, synchronous motors are still significantly more expensive than induction motors, whereas their small time constants, mechanical properties and high torque values, currently determine their use in positioning drives.

In induction motor drive systems there are two basic methods of frequency speed control: scalar and vector control. Classical scalar control methods, due to their properties, are used only in drives of low responsibility. The most popular method is control with forced stator voltage in which the so called intermediate flux stabilisation is obtained by keeping the ratio U_s/f_s constant. A schematic diagram of this common structure is presented in Fig. 5 [6].

From the point of view of the possibilities of shaping the electromagnetic torque of a drive, it is a system with direct voltage enforcement and as such, even after using speed feedback, it does not ensure good dynamic properties of torque control. The system, outside the obvious advantage of its simplicity, has a lot of disadvantages visible in transient states, such as: no torque and current control, long transient states. Regardless of this, scalar control systems have found their place in among industrial drives of medium requirements and are extensively used in installations which should be simple and speed regulation must be inexpensive [6], [8].

Whenever the quality of drive regulation has a decisive influence on a technological process or product, currently vector control methods of induction motor torque and speed are used [6]–[8]. Two basic strategies are distinguished in vector control:
- Field Oriented Control (FOC) [9], [10],
- Direct Torque Control (DTC) [11], [12],

in which the position of the vectors of basic electromagnetic values of a machine (voltages, currents, fluxes) are impacted, which ensures their correct orientation in both static and dynamic states. It also completely eliminates the disadvantages of scalar control and ensures the static and dynamic properties of an induction drive which are analogous to the ones obtained in inverter drives with DC motors controlled in a cascade structure [6].

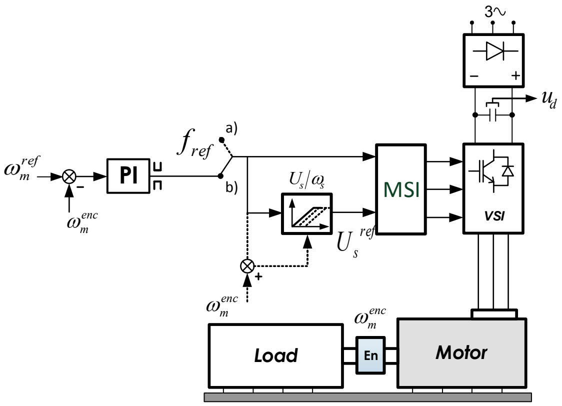

Fig. 5. Schematic diagram of a scalar structure of motor speed control:
(a) open system, (b) closed system

As early as the beginning of the 1970's the fundamentals of the vector regulation of induction motors were established, however, their full verification was not possible until the end of the 20th century when the development of microprocessor systems allowed for it. The basics of the Direct Field-Oriented Control method (DFOC) were developed by F. Blaschke in 1972 [9]. A characteristic feature of this method is the necessity to have access to information about the current value and position of the rotor flux vector in regard to which the control of stator current vector components are oriented. This information can be obtained thanks to various types of estimators using physical properties of electrical machines or based on algorithmic methods, such as: simulators, state variable observers and Kalman filters [6]–[8]. The key advantage of this control structure are its very good dynamic properties.

An alternative for this method is the Indirect Field-Oriented Control (IFOC) system proposed by K. Hasse in 1972 [10]. This method is characterised by an indirect way of determining information about the current position of the rotor flux space vector on the basis of the measured value of angular speed and the calculated value of rotor slip. The accuracy of determination of this pulsation significantly depends on time constant changes of rotor winding, which results in degradation of system dynamic properties in the case of frequent speed changes of a drive and also in the range of low values of the set rotor speed.

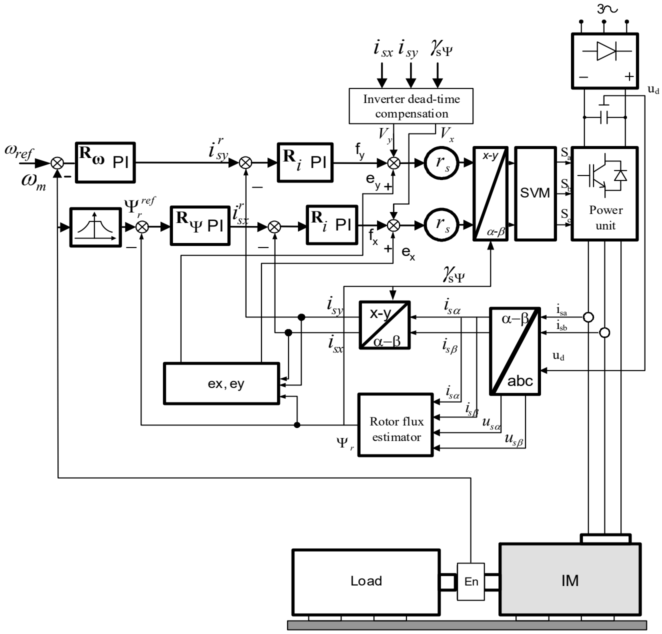

Fig. 6. Scheme of the Direct Field-Oriented Control structure with an induction motor (DFOC)

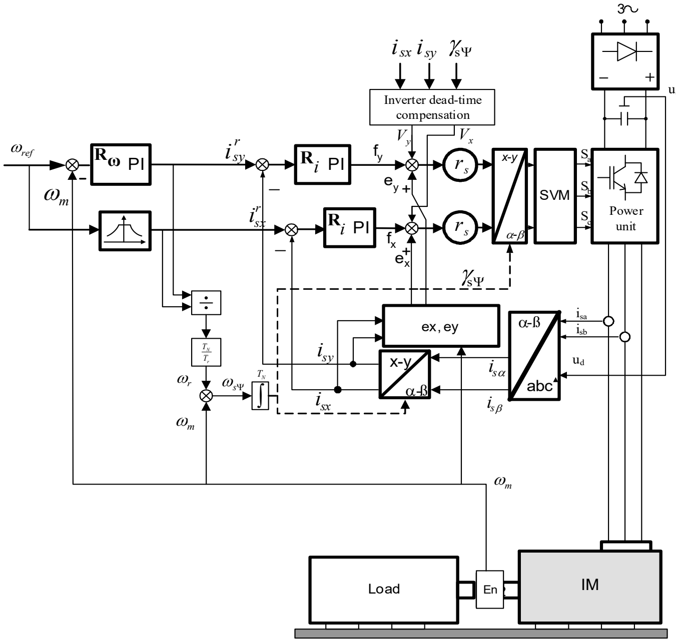

Fig. 7. Scheme of Indirect Field-Oriented Control structure with an induction drive (IFOC)

Moreover, the amplitude of a rotor flux is not directly stabilised. Thus, regardless of the relatively simple possible implementation and the lack of a rotor flux estimator [6], currently the structure is not widely used in industrial drive systems with high dynamic requirements. Schematic diagrams of DFOC and IFOC systems with a rotor angular speed sensor are presented in Figs. 6 and 7.

The DFOC method enables stable operation of a drive for both very small values of angular speed and values exceeding the rated speed. However, a downside of this method is its relatively complex control structure (necessity to transform coordinate systems, realization of a rotor flux estimator) and dependence on induction motor parameters, which makes it sensitive to machine parameter changes. However, the structure offers extensive implementation possibilities in sensorless drives because the information about the value and position of the rotor flux vector can also be used to estimate the rotor angular speed. It is constantly being developed until today and it is frequently used in various industrial applications.

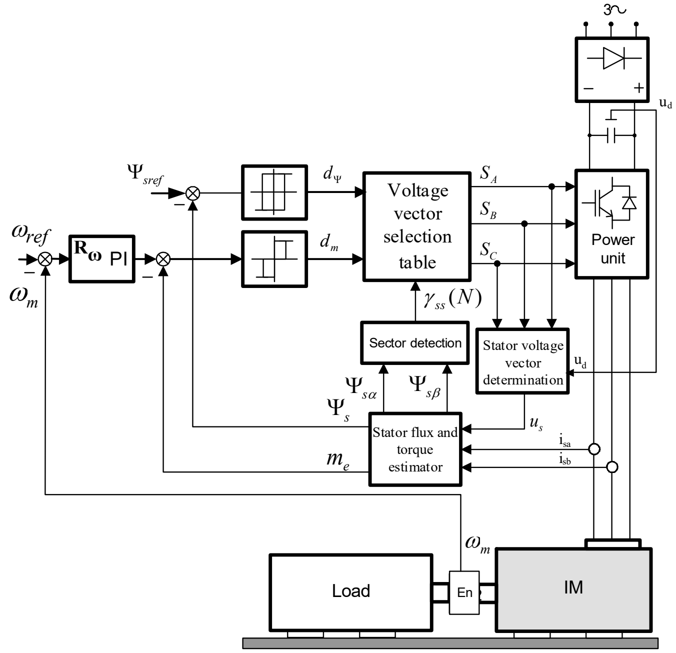

Fig. 8. Scheme of a Direct Torque Control structure (DTC)

Another approach to induction motor control is the Direct Torque Control (DTC) method first proposed by I. Takahashi [11]. It is based on a direct connection between the electromagnetic torque and stator flux SI with stator voltage generated by a frequency converter with a voltage inverter MSI. Thanks to this it is possible to directly and very quickly control the electromagnetic torque of a machine. A scheme of the basic DTC structure is presented in Fig. 8. A detailed description of this control method can be found in numerous available books, e.g., [6], [8].

Owing to its very simple structure and low hardware requirements, the DTC structure has a significant position in industrial drive systems with induction motors. The possibility of very quick control of electromagnetic torque resulted in the fact that for a long time this method was practically beyond any competition in terms of its dynamic properties. Unfortunately the basic structure, regardless of its relative simplicity, has a disadvantage, namely variable frequency of connections between voltage inverter transistors and the resulting losses in the system depend on the specifics of drive operation (regulation range, load variability, operation type). As a result in the last decade research was conducted to find a method which would maintain all advantages of DTC and at the same time eliminate this downside.

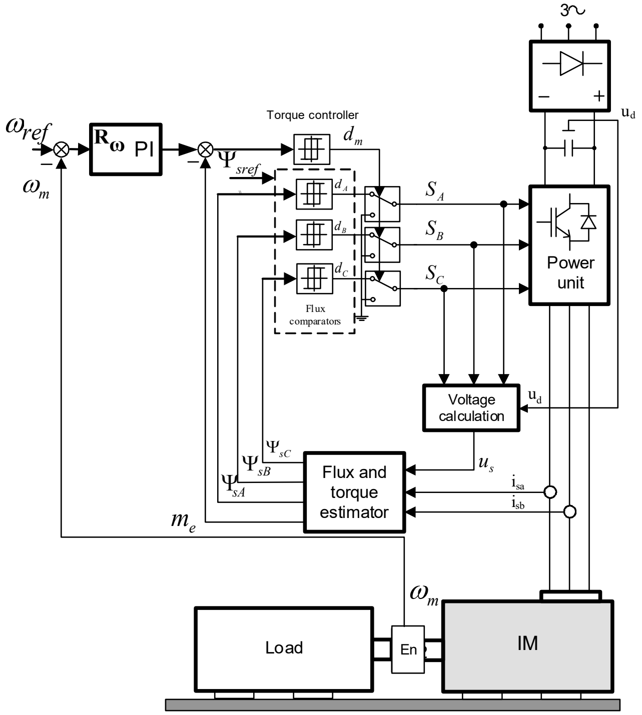

Fig. 9. Scheme of the DSC structure

The Direct Self Control (DSC) method dedicated to large power drives was proposed by M. Depenbrock [12], it also employs the idea of electromagnetic torque control through direct control of stator voltage. A scheme of this structure is presented in Fig. 9. Regardless of very good dynamic properties of a drive system controlled by

DSC, it cannot be used in systems requiring high accuracy in torque or speed control, neither can it be used in sensorless drives. Low frequency of inverter valve connections results in great deformations of a stator current, which in turn is the reason for significant pulsation of the motor torque and faulty or even instable estimation of angular speed in the range of small and big angular speeds. A similar phenomenon occurs in classical DTC systems.

Very good dynamic properties and constant frequency of inverter connections as well as small deformations of stator current can be obtained by using modified algorithms of direct torque control with vector modulation in the so called Direct Torque Control–Space Vector Modulation (DTC–SVM) methods [8]. A scheme of one of such methods is presented in Fig. 10.

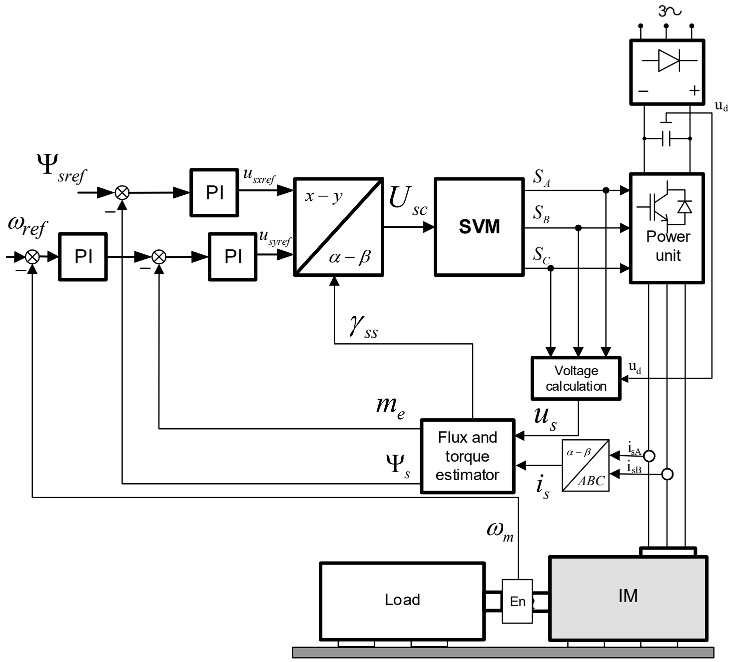

Fig. 10. Scheme of the DTC–SVM structure

With the development of control methods based on the DTC concept, these systems are becoming increasingly complex and dependent on the parameters of the substitute scheme of an induction motor. One can state that the latest DTC–SVM control methods more and more resemble the classical DFOC method. The transformation of a coordinate system, rotor and/or stator flux estimation blocks become necessary for their correct operation, and their internal structure frequently uses the mathematical model of a machine used to calculate the right amplitude values or the position angle of the flux vector. The method can be successfully used in complex industrial applications – mainly in drives requiring fast changes of electromagnetic torque and in servo drives.

On the basis of literature analysis and own experience of the authors, the evaluation of the methods of induction motor torque and speed control was conducted. The possibility of using a given control method without a rotor angular speed sensor was analysed, too.

Table 1. Comparison of vector control methods of an induction motor

	IFOC	DFOC	DTC	DSC	DTC–SVM
Dynamic properties	Poor	Good	Very good	Very good	Very good
Static properties	Good	Very good	Good	Average	Good
Connection losses	Small	Small	Big	Big	Small
Current THD	Small	Small	Big	Very big	Small
Calculation complexity	Average	Big	Small	Small	Big
Dependence on SI parameters	Very big	Very big	Small	Small	Very big
Properties at low speed	Poor	Very good	Average	Poor	Good
Properties at high speed	Good	Very good	Good	Good	Very good
Modulator	Yes	Yes	No	No	Yes
Universality	Small	Big	Big	Small	Big
Level of difficulty in tuning	Medium	Medium	Simple	Very simple	Medium
Operation quality in sensorless operation	Poor	Very good	Average	Poor	Very good

The outcomes of the analysis are collected in Table 1. On the basis of the analysis (Table 1) one can unequivocally state that the DTC–SVM and DFOC methods, regardless of their complex structure and rather high hardware requirements, are characterised by very good dynamic properties and low connection losses, and so they can be successfully used in various types of drive systems.

In the case of drives with permanent magnet synchronous motors one can distinguish two basic control structures depending on the construction and type of feeding in a motor [1], [6], [13], [14]:

- drive system with the so called Brushless DC Motor (BDCM), with trapezoidal SEM distribution, Fig. 11a;
- drive system with the Permanent Magnet Synchronous Motor (PMSM), with sinusoidal SEM distribution, with vector control (Fig. 11b).

The BDCM system is characterised by simple control, however, due to worse dynamic properties and torque pulsations caused by quasi-rectangular stator current waveforms, it is used when speed and position regulation requirements are lower (after complementing the structure with an additional control loop).

The PMSM control structure is a typical vector control structure – field-oriented, as shown in Fig. 11b or DTC (Direct Torque Control) and, as a result, it ensures excellent dynamic properties, torque, speed and/or position control [14]. PMSMs should be used whenever perfect accuracy parameters and good dynamics are prerequisite and when it is economically justified.

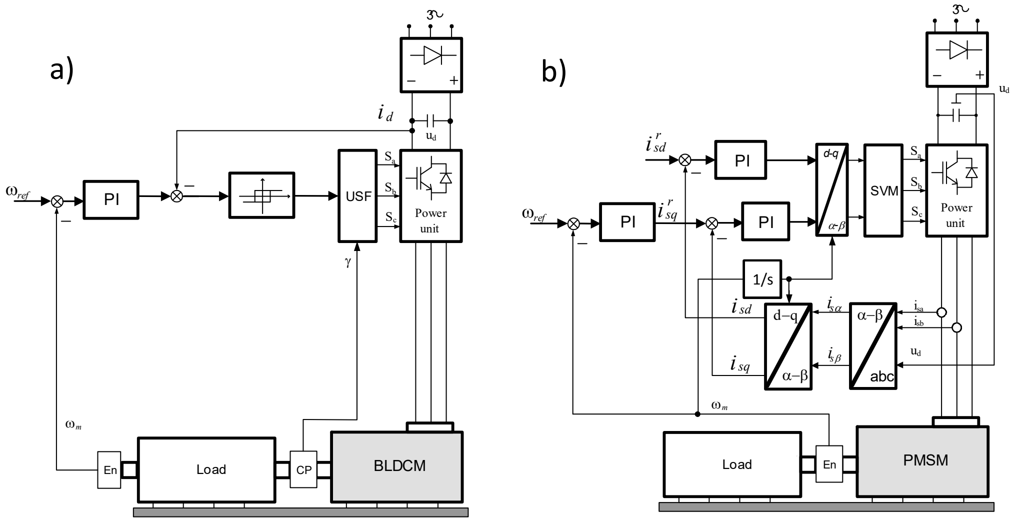

Fig. 11. Schematic diagram of inverter drive systems with synchronous motors: (a) BLDCM; (b) PMSM

Apart from the above mentioned motors and control methods, in recent years one could observe intensive development of Switched Reluctance Motors (SRM). These machines have a great potential, in particular, in solutions dedicated to electric vehicles [15]. It seems, however, that they are not a competition for PMSMs, they are only a kind of alternative with particular properties and parameters.

It should be noted that vector methods have recently become a standard used not only to control torque and speed of an AC motor fed by an PWM voltage inverter, but also in network converters with SVM to obtain the highest (unity) power factor on the converter system input [16]. It is possible to observe intensive development of control methods for network converters feeding PWM inverter systems and the transformation from traditional diode solutions to the controlled ones, also using the PWM method, transistor input converters.

Currently the most popular methods of vector control of induction motors fed by FOC and DTC transistor inverters correspond with Voltage-Oriented Control (VOC) methods (Fig. 12) and Direct Power Control (DPC) methods (Fig. 13) for network converters [16]. Similarly to the Field-Oriented Control of induction motor torque, in which the selected *x*-*y* coordinate systems must be rotor flux vector oriented, in the case of output voltage control of a transistor converter, the network current control is virtual flux Ψ_g (virtual induction machine) oriented, as shown in Fig. 12, or voltage oriented.

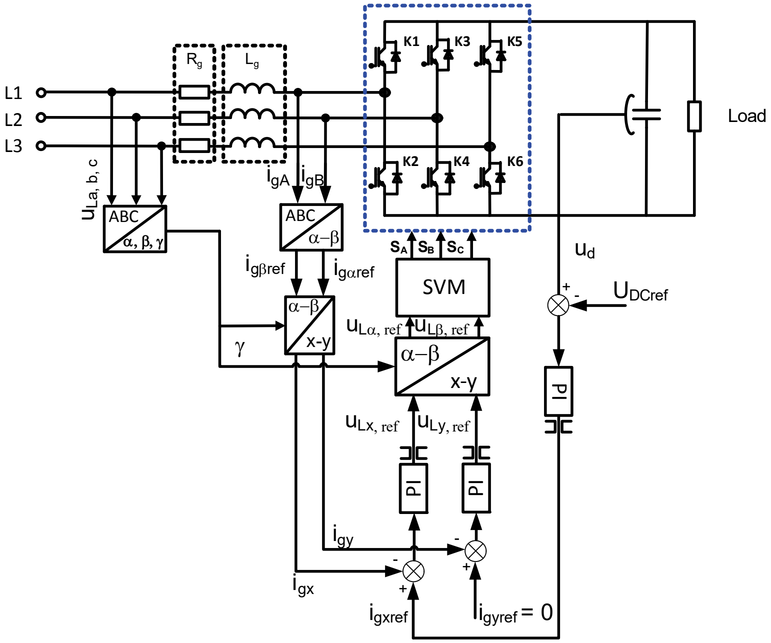

Fig. 12. Schematic diagram of Voltage Oriented Control (VOC)

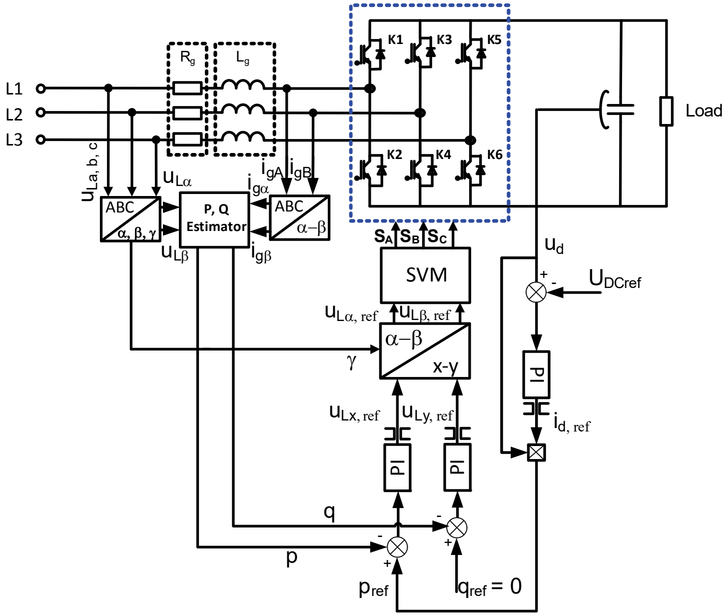

Fig. 13. Schematic diagram of voltage-based direct power control of support vector machine (VDPC-SVM)

The vector component i_{gx} of network current determines passive power while the component i_{gy} determines active power, i.e., it is possible to obtain independent control of active and passive power flow. With the enforcement of $i_{gx} = 0$ in the control system, one obtains the minimum current use from the network and unity power factor and output voltage control U_{DC} of the network converter. In the system presented in Fig. 13, the required instantaneous values of active and passive power are calculated on the basis of the network voltage vector or the network virtual flux vector.

Table 2. Comparison of vector control techniques of PWM converters

Method	Advantages	Disadvantages
VOC	– constant connection frequency – possibility of using advanced PWM techniques – cheaper A/C converters	– coordinate transformation and control circuit decoupling with an active and passive component are required – complex algorithm – power input factor is higher than in the case of VDPC
V-DPC	– modulator not needed – no current regulation circuits – coordinate transformation not needed – good dynamics – control circuits decoupled with active and passive power – state variables are estimated with harmonic components (improved cosφ and efficiency)	– variable connection frequency – higher inductivity values and sampling frequency are necessary (smoother current which is important for an active and passive power estimator) – power and voltage estimation should be avoided during valve switching – fast microprocessors and A/C converters are necessary
VFOC	– constant connection frequency – possibility of using advanced MSI techniques – cheaper A/C converters	– coordinate transformation and control circuit decoupling with an active and passive component are required – complex algorithm – input cosφ lower than in VF-DPC
VF-DPC	– simple power estimation, easy implementation – lower sampling frequency than in V-DPC – modulator not needed – no current regulation circuit – coordinate transformation not needed – good dynamics – control circuits decoupled with active and passive power	– variable connection frequency – fast microprocessors and A/C converters are necessary

The control structures presented in Figs. 12 and 13 are possible solutions as currently four control strategies of MSI control converters are distinguished [16]:

- voltage-oriented control (VOC),
- voltage-based direct power control (VDPC),

- virtual-flux oriented control (VFOC),
- virtual-flux-based direct power control (VFDPC).

Similarly to the vector control of an induction motor, here also it is possible to compare the properties of these four strategies of converter control. Such a comparison is presented in Table 2, which shows that experience connected with the methods of decoupled control of induction motor torque was used in decoupled control of network converter power [16].

Moreover, thanks to the development of digital and microprocessor technology, in systems whose parameters are uncertain or change in extensive ranges the classical PID type control is more and more often replaced by fuzzy or neuro-fuzzy (self-learning), predictive, slip regulators [17]–[20]. In the near future these solutions will also be an option in standard converter systems used to feed drive systems.

In accordance with predictions made about ten years ago, a contemporary, advanced drive of the 21st century meets not only all the requirements connected with various control functions, but also the requirements connected with natural environment protection (energy quality, electromagnetic interferences), monitoring and diagnostic functions and communication with surroundings. A schematic diagram of such a drive is presented in Fig.14. Such a drive has a power input and output as well as control and communication inputs (wiring or wireless) with functions appropriately selected and parametrised by a user. Manufacturers of such drives take special care to make sure that the control panel is easy to use, regardless of the complexity of a selected control system. Converter drives are becoming more compact and more configurable in terms of both hardware and software aspects. Modern solutions related to integrated safety systems and energy-efficient algorithms are introduced. Communication between supervision and process quality control systems is possible.

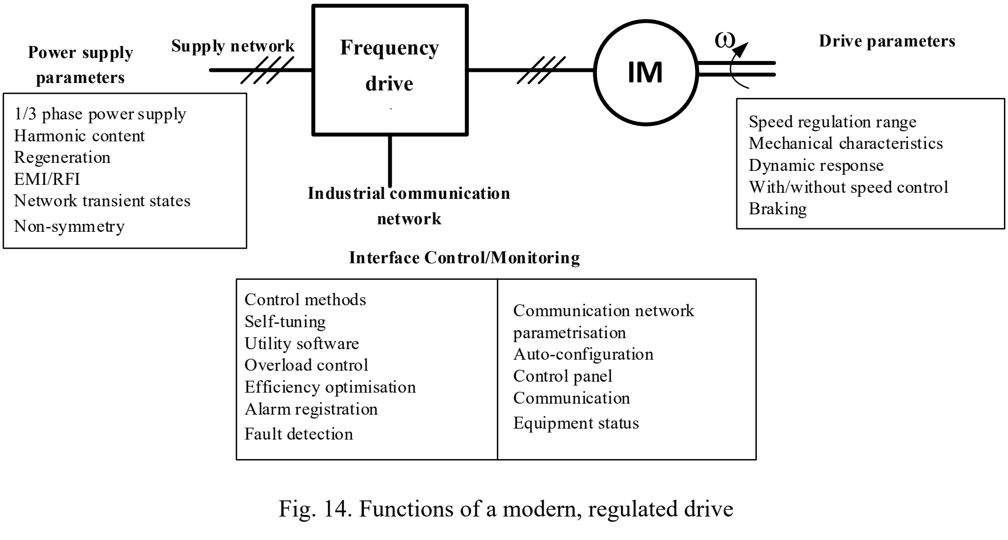

Fig. 14. Functions of a modern, regulated drive

In accordance with users' expectations, frequency converters for AC drives are equipped with specialist software allowing one to make structures and perform control functions dedicated to specialist applications related to positioning, concurrent regulation, multiaxial control without any necessity to use other devices. In numerous solutions there are integrated PLCs, CAN Open industrial network connectors, Ethernet control. Most of the regulated drives with improved static and dynamic properties allow braking energy to be regained, which in the case of connecting other drives to the same, common supply circuits makes it possible to significantly save energy.

In the near future even the standard equipment of drive systems for simpler applications, such as ventilation and pumping systems, will encompass simple interfaces facilitating process service and selftuning of drive parameters. In advanced drives there will be solutions which, apart from increasingly better dynamic properties (response time of regulated value: torque, speed or positioning thanks to the use of improved regulator control and tuning methods), will also include additional functions, such as: vibration reduction, stabilisation accuracy in a small speed range, possible elimination of speed and/or positioning sensor (sensorless drives), elimination of redundant wiring connections in control cabinets thanks to the use of a common data circuit for all drive components and extended safety functions (monitoring, diagnostics and fault compensation).

The above mentioned development trends of converter drives will lead to improvement of energy efficiency of equipment and hence a decrease in machine exploitation costs and improved manufacturing process efficiency and safety.

3. FAULT TOLERANT SYSTEMS

Among the above mentioned development trends of contemporary electric drives, tolerance of selected faults, their detection and compensation during drive operation are some of the currently most extensively developed issues in various research and industrial centres. In addition to this, the notion of fault tolerant systems means that in the case of a fault of one of its components such a system can use mechanisms which will allow fault type and place to be detected, fault compensation or drive structure reconfiguration to allow for safe stoppage of a damaged technological process.

Growing requirements related to the properties of electrical drives led to significant complexity of their structures and at the same time greatly increased fault risk. A contemporary converter drive system (CDS), composed of an AC motor, power supply and power electronics systems, measurement systems and a digital control system, is prone to a number of faults related not only to the motor itself, but mainly the frequency converter and measurement sensors.

Over 80% of CDS faults are caused by abnormalities in the operation of IGBT transistor connectors, namely short circuits or short/open switch faults [21], [22]. The most common reason for this type of faults is drive overuse which leads to converter overload. A short circuit of one connector always leads to the damage of a power converter and current stoppage. On the other hand, no conductivity of a transistor connector can be detected and quickly compensated because it inevitably leads to the occurrence of current strokes and electromagnetic moment damaging a drive. A frequency converter fault should not lead to an instantaneous current stoppage, which currently is usually the case. It is possible to use appropriate redundancy in the structure of the power electronic module, however, this would be connected with a significantly higher cost of a converter [22]. This is why there is such interest in control strategies allowing a faulty connector to be isolated and the modulation algorithm to be changed for the purpose of safe stoppage of the system without any emergency stopping of a technological process.

The second group are measurement system faults. This kind of devices differ depending on the type of sensor used. There are the following faults of sensors of electrical values: breaking measurement loop, offsets of a constant component, saturation, measurement noises and gain errors. In the case of sensors of mechanical values (most often a rotational speed sensor is the case) there are such faults as: no output impulse caused by breaking a feedback loop, incorrect number of impulses, cyclically broken output signal [23].

The third type of CDS faults are the faults of machinery coils (stator coil short circuits, cracking of rotor cage bars and rings) or mechanical elements (faults of bearings and clutches, misalignment) [21], [24].

In the case of monitoring a CDS, it is especially important to quickly locate a faults and next compensate its consequences. Figure 15 presents the order of actions in the case of a fault tolerant CDS.

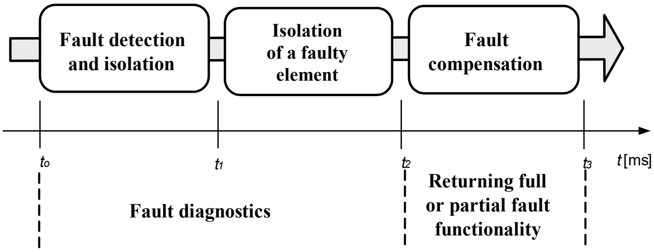

Fig. 15. Sequence of actions in a fault tolerant CDS

The methods of fault detection, identification and compensation should be used in real time so as to verify measurements in the shortest possible time for the purpose of diagnosing a fault and take appropriate steps [7], [21]–[24]. This means additional difficulties in the development of a feasible solution due to limited computing power and available memory of processors used in diagnostics and control systems [25].

Fault Tolerant Control Systems (FTCS) can be divided into two types: passive and active ones [25], [26] (Fig. 16).

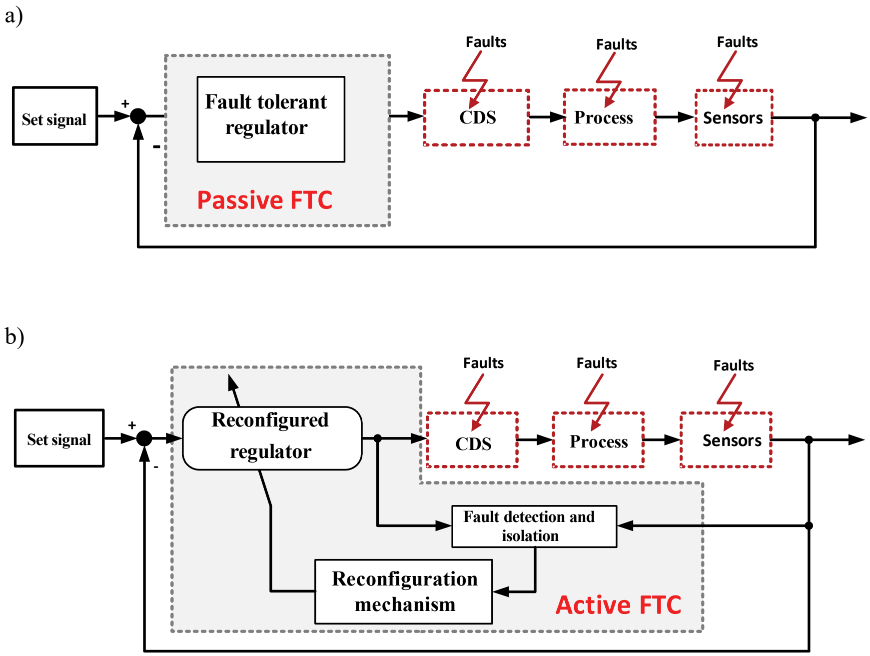

Fig. 16. General structure of Fault Tolerant Control Systems (FTC): (a) passive system, (b) active system

Passive systems are designed in such a way as to ensure optimum efficiency in case of a certain number of faults without the necessity to acknowledge their occurrence [25], [26]. Passive fault resistant systems apply control techniques (e.g., adaptation, slip) which ensure that the controlled system in a closed loop remains insensitive to certain faults, in such a way that a faulty process is continued maintaining the same control structure and parameters. Such approach is supported by two arguments. Firstly, obtaining such compensation is possible by using simple software and hardware configuration, and secondly, according to the classical reliability theory, system stability decreases abruptly with an increase of system complexity. This is why the main goal of passive fault tolerant system is gaining advantage over classical control structures by efficiency improvement as well as designing and making less complex systems.

However, active fault resistant systems (Fig. 16b) use detectors and/or observers [25], [26] which detect faults. In this case the main goal is regaining efficiency by using additional redundant circuits or by adapting regulator and estimator parameters as a result of new control object identification. Contrary to passive fault resistant systems, instead of depending on constant control system insensitivity to any possible situation, active FTCs react to faults by adapting parameters and regulation conditions. For the purpose of achieving a desired reconfiguration or restructuring, a system requires either a set of information about a fault or an appropriate mechanism for fault detection and isolation [21]–[26].

There is no doubt that using solutions characteristic of fault tolerant drive systems results in:

- minimisation of process exploitation costs by ensuring continuity of drive operation, limiting negative consequences of faults, a possibility of automatic diagnosis (in the case of active FTC systems);
- high degree of safety by maintaining system stability even when a fault occurs;
- autonomy and certainty of operation by guaranteeing the completion of complex tasks and setting a new quality standard.

4. CONCLUSIONS

It should be expected that, combined with new technological and construction related solutions for electrical machines, development trends of electric drives will follow the direction of more accurate control adapted to drive operating conditions and ensuring optimum adaptation to the requirements of executive systems.

There is no doubt that in most industrial applications the future will belong to AC motor drives fed by frequency converters with network converters and voltage converters made using smart power modules controlled by the MSI method. Systems with low dynamic requirements will use simple integrated drives with scalar control methods. In the case of more responsible systems, the nearest future will belong to multifunction (in terms of interfaces: power input and output, control and communication) converter drives with vector control using various regulators: classical PID, slip, fuzzy, neural, including adaptive ones.

Sensorless drives will be used in such applications as manipulators and industrial robots, in this case direct measurement – especially of mechanical feedback signals – will be replaced by reproduction of state variables using algorithmic and/or neural estimators with high tolerance to changes and erroneous identification of motor parameters. Moreover, the dominating trend in industrial solutions will be drives with an increased safety degree.

Many of the presented methods and techniques of electric drive control as well as problems connected with the diagnostics and isolation of selected faults require further research and solution optimisation before they can be implemented to industrial practice and become a standard in drives available on the market.

REFERENCES

[1] ORŁOWSKA-KOWALSKA T., *State of the Art and Future Development of Electrical Drives*, Przegląd Elektrotechniczny, 2004, Vol. 80, No 3, 185–190, (in Polish).

[2] FINCH J.W., GIAOURIS D., *Controlled AC Electrical Drives,* IEEE Trans. Industrial Electronics, Vol. 55, No. 2, 481–491, 2008.

[3] HERMANN, PENTEK, OTTO, *Design Principles for Industrie 4.0 Scenarios*, 2015.

[4] CIENIAK I., *Polish market of electric drives and servodrives*, Control Engineering Polska, 2011, (in Polish).

[5] SCHWAB K., *The Fourth Industrial Revolution*, 2016.

[6] ORŁOWSKA-KOWALSKA T., *Sensorless induction motor drives*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2003, (in Polish).

[7] DYBKOWSKI M., *Estimation of Speed in a Vector Controlled Induction Motor Drive – Selected Problems*, Scientific Papers of the Institute of Electrical Machines, Drives and Measurements of the Wroclaw University of Technology, ser. Monographs, Vol. 20, Wrocław 2013, (in Polish).

[8] KAZMIERKOWSKI M.P., BLAABJERG F., KRISHNAN R., *Control in Power Electronic – Selected Problems*, Academic Press, USA, 2002.

[9] BLASCHKE F., *The principle of field orientation as applied to the new TRANSVECTOR closed-loop control system for rotating field machines*, Siemens Review, 1972, No. 34, 217-220.

[10] HASSE K., *Drehzahlgelverfahren fur schnelle Umkehrantriebe mit stromrichtergespeisten Asynchron-Kurzchluss-laufer-motoren*, Reglungstechnik, 1972, No. 20, 60–66.

[11] TAKAHASHI I., NOGUCHI T., *A new quick response and high efficiency control strategy of an induction motor*, IEEE Trans. Industry Applications, Sept/Oct 1986, Vol. IA-22, No. 5, 820–827.

[12] DEPENBROCK M., *Direkte Selbstregelung (DSR) fuer hoch dynamische Drehfeldantriebe mit Stromrivhterschaltung*, ETZA, 1985, Vol. 7, 211–218.

[13] KRYKOWSKI K., *PM BLDC Motor in Electric Drive. Analysis, Properties, Modelling*, Wydawnictwo Politechniki Śląskiej, Gliwice 2011, (in Polish).

[14] ZAWIRSKI K., *Control of Permanent Magnet Synchronous Motor,* Wydawnictwo Politechniki Poznańskiej, Poznań 2005, (in Polish).

[15] GIERAS J.F., GIERAS I.A., *Electric motors – the future*, Proc. of 9th Int. Conf. on Power Electronics and Motion Control, PEMC'2000, Kosice, Slovak Republic, 2000, 1.12–1.18.

[16] MALINOWSKI M., *Sensorless Control Strategies for Three-Phase PWM Rectifiers*, Doctoral Thesis, Warsaw University of Technology, Warszawa 2001.

[17] SZABAT K., ORŁOWSKA-KOWALSKA T., DYBKOWSKI M., *Indirect Adaptive Control of Induction Motor Drive with an Elastic Coupling*, IEEE Trans. Industrial Electronics, 2010, Vol. 56, No. 10, 4038–4042.

[18] ORŁOWSKA-KOWALSKA T., TARCHAŁA G., DYBKOWSKI M., *Sliding-Mode Direct Torque Control and Sliding-Mode Observer with magnetizing reactance estimator for induction motor drive*, Mathematics and Computers in Simulation, Vol. 98, 2014, 31–45.

[19] KAMIŃSKI M., ORŁOWSKA-KOWALSKA T., *Adaptive Neural Speed Controllers Applied for a Drive System with an Elastic Mechanical Coupling – a Comparative Study*, Engineering Applications of Artificial Intelligence, October 2015, Vol. 45, 152–167.

[20] WRÓBEL K., SERKIES P.J., *Predictive position controller for the induction motor drive*, Poznań University of Technology Academic Journals, Electrical Engineering, 2015, No. 83, 169–176.

[21] KOWALSKI C.T., *Diagnostics of the Induction Motor Drives using Artificial Intelligence Methods*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2013, (in Polish).

[22] ORŁOWSKA-KOWALSKA T., SOBAŃSKI P., *Simple diagnostic technique of single IGBT open-circuit fault in SVM-VSI vector-controlled induction motor drive*, Bulletin of the Polish Academy of Sciences, Technical Sciences, 2015, Vol. 63, No. 1, 281–288.

[23] KLIMKOWSKI K., DYBKOWSKI M., *Analysis of vector controlled induction motor drive robust to chosen sensor faults*, Poznań University of Technology, Academic Journals, Electrical Engineering, 2014, No. 77, 193–200.

[24] WOLKIEWICZ M., TARCHAŁA G., KOWALSKI C.T., *Stator windings condition diagnosis of voltage inverter-fed induction motor in open and closed-loop control structures,* Archives of Electrical Engineering, 2015, Vol. 64, No. 1, 67–79.

[25] ISERMANN R., *Fault Diagnosis Systems. An Introduction from Fault Detection to Fault Tolerance*, Springer, New York 2006.

[26] JIN JIANG, XIANG YU, *Fault-tolerant control systems: A comparative study between active and passive approaches*, Annual Reviews in Control, April 2012, Vol. 36, No. 1, 60–72.