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FAULT DETECTION IN POWER ELECTRONICS SYSTEMS BASED ON QUALITATIVE AND QUANTITATIVE MODELS

SUMMARY *It is assumed in this paper that monitoring both the converter and its control states means continuous formulation (i.e. in a repeatable way) of a diagnosis of the plant's state automatically via a suitable computer diagnostic system. In other words it is on–line diagnosing carried out in real time. The authors assume that mainly the operating signals are used for diagnostic purposes since it is not recommendable to disturb the process with any additional test signals.*

Implementation of the orthogonal expansion made it possible to depict the system state approximated by a sequence of its values' observations in a form of some linear combination of basic functions. Complete families of binary orthogonal Walsh and Haar functions are employed. The employed research methods may be considered numeric-analytical ones. The investigation of the signal properties in power electronics inverters was carried out using fast processing algorithms (both in serial and parallel modes).

Along with the simulational modeling the presented approach made it possible to execute a complex fault detection and isolation for a typical arrangement of the inverter. The fast transform algorithm used in this paper is based on the Haar matrix factorization.

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1. INTRODUCTION

Diagnostic systems should be capable of fault isolation and identification at different stages of its growth. In case of industrial conditions it frequently appears that without monitoring or performing the diagnostic procedure appropriately a complex electromechanical or power electronics system is not able to accomplish the tasks imposed by the technological regime or the user. Unexpected breakdowns cause disorder in operation of the plant and bring considerable losses in production volume. It is obvious that an early recognition of the power electronics inverter's dynamic state, or the extent to which its components are worn, is essential. Monitoring the state of the machine and/or the power electronics equipment makes it possible to state their expected lifetime as well as avoid the cost of unnecessary overhauls.

An integrated diagnostic system for a drive should comprise both the machine and the inverter. In case of e.g. a typical voltage source inverter (VSI) a drive system comprises four subsystems at least: the machine, the rectifier, the inverter and the control. Reviewing the relevant literature it may be seen that considering the inverters intended for the commercial drives there is a relatively small number of their structure configurations. Similar topologies of the power electronics systems should lead to similar results for typical faults. Therefore quite often there are chances to design a diagnostic system irrespective of the inverter's brand and specifications.

Spectral analysis is a basic tool for diagnostic purposes and each additional line appearing in the spectrum becomes a potential diagnostic indicator [9]. The goal of such an analysis should be a set of rules for the diagnostic system knowledge base. Of course an effective system should provide an a priori information about even minute element faults emerging, since it is known from the practice that their early detection permits to avoid costly disastrous events. In this context the parameters of the switching elements should be monitored. This is a difficult task, since according to the relevant research the problem should be solved by trend analysis [4].

Algorithms accomplishing these functions in the inverter's diagnostic system make use of current and voltage values in the form of time sets, as well as of other digital control and binary logic signals. All these signals should be preprocessed to check their reliability. This is accomplished employing verification procedures. The goal of this verification, which should make use of information redundancy, is detecting possible errors in the digital form of the signals [16]. The verification system should rectify any detected errors.

2. SIGNAL PROCESSING IN DIAGNOSTICS OF POWER ELECTRONICS SYSTEMS

Diagnostic tasks performed in power electronics equipment by dedicated diagnostic systems may be divided into:

1. Diagnostics of the technological process – bound up with recognition of the abnormalities within the inverter, its valves, motor and associated measuring equipment;
2. Diagnostics of the control system – connected with recognition of faulty regulators, programmable logic controllers, or local area networks, linking the control and the plant.

It must be noted, however, that microprocessor regulators or programmable logic controllers are usually accompanied by diagnostic measures providing fault detection and isolation.

The term ‘diagnosing power electronics system’ as used in this paper is to be understood as accomplishing a set of tasks, whose goal is recognition of the system’s current technical state and making relevant conclusions about this state. By the ‘state of the plant’ these authors will mean the least set of variables, such one that knowing it and knowing the future behavior of the control quantities it is possible to determine the future behavior in time of the power electronics system’s output variables. A ‘fault’ will be understood hereafter as an event that shifts the plant under control from the normal operating condition into the state of inferior working condition. Therefore diagnosing will mean a process of fault detection and isolation being a sequel of acquisition and processing of the data on the plant, e.g. as a result of analysis and both qualitative and quantitative evaluation of diagnostic signals.

Like in [6] the present authors distinguish three stages in diagnosing the state of a power electronics system:

1. Fault detection – i.e. taking notice of its appearance at a certain time instant,
2. Fault isolation – i.e. determining the nature and place of its occurrence,
3. Fault identification – i.e. recognition of the size and nature of the fault variability.

3. SIGNAL MODELS AND DIAGNOSTIC TESTS IN POWER ELECTRONICS

The physical phenomena occurring in power electronic systems are continuous in nature, while in digital diagnostics discrete signals are used. The degree to which the analog voltage and current signals in power electronic equipment are distorted usually increases together with its complexity. So there are phenomena like voltages and currents disturbed with harmonic and aperiodic components, the symmetry disturbed in three phase systems, a.s.o. From the point of view of the system's reliable operation it is essential to define which signal components contain useful information and which do not. Therefore more significant are the systems that can sooner detect the occurring faults. The main field where diagnostic systems are employed are disturbances in the power supply and/or valve control, damages in the insulation, and so on.

Depending on what are the chances to distinguish the nature of each signal component one can set up different types of the signal models under consideration. Considering different types of models, that usually contain both useful and unusable information, one can enumerate the following signal models: a deterministic and a probabilistic one (partially or fully).

In the deterministic model both the useful signals and disturbances are considered deterministic functions of time, while their parameters may be unknown. In a partially probabilistic model it is usually assumed that the signal components are deterministic in nature, and the error signal behaves like a random process of known features (e.g. white noise of known power spectral density). The optimum principle of digital signal processing may be derived from this, consisting in minimization of variance of voltages and currents estimation errors. A fully probabilistic model is featured by useful signals, disturbances and error signals being probabilistic in nature. In this case the most convenient way to present such a model is the mathematical one in the form of discrete equations of the state variables, in which the optimum estimation of the state vector components leads to the Kalmann filter.

In some cases the voltages and currents of the power electronics system under diagnose may be rendered exclusively as sets of realizations [15]. Then suitable approximation procedures may be employed in order to extract the analytical form.

In the simplest case a diagnostic signal may be either the value (in the time domain) or spectral characteristic (in the frequency domain) of a state variable. To get a valuable information the state variables are processed. The following schemes are employed then:

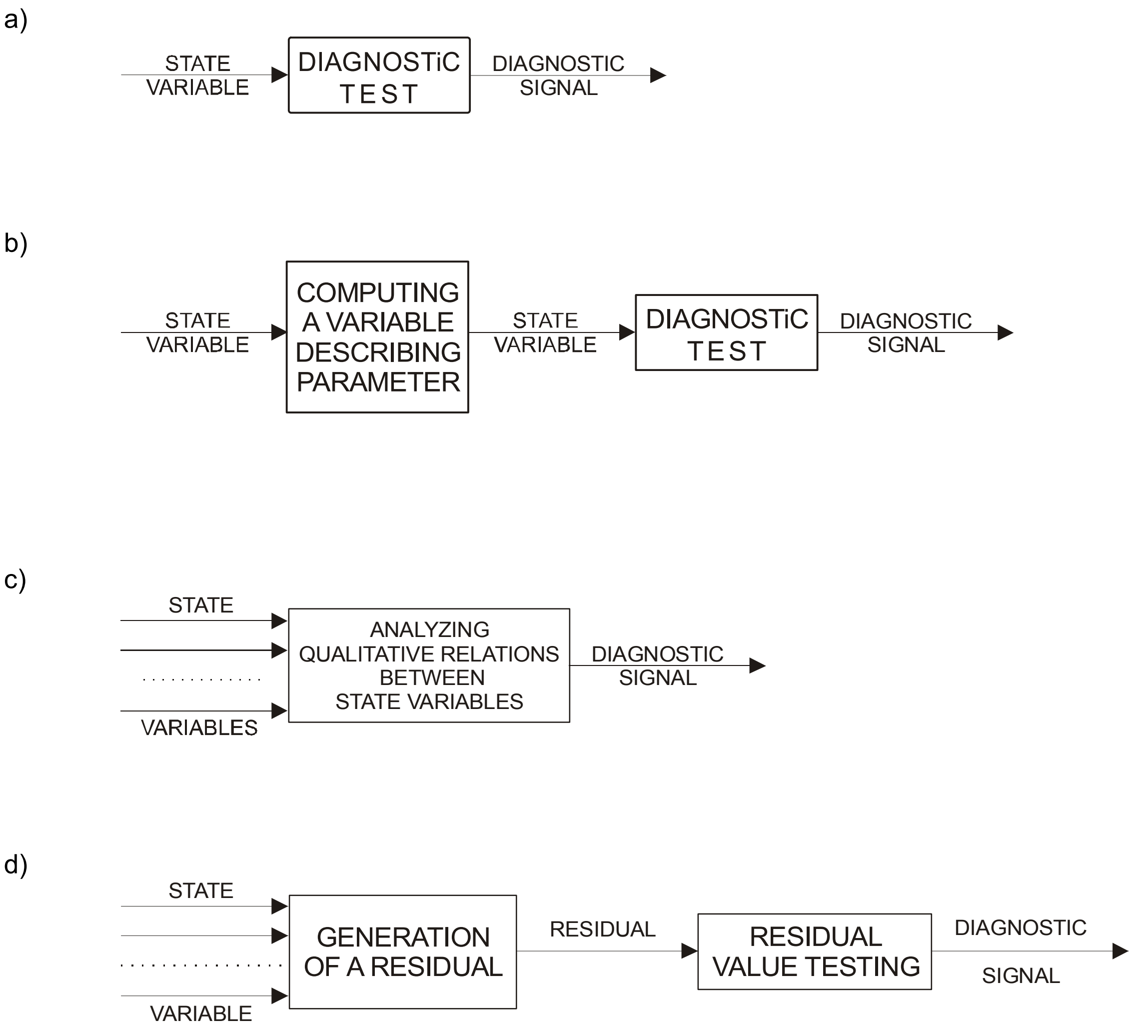

Fig.1. Feasible diagnostic tests in evaluation of the state variables.

In case a) the diagnostic signal is determined in the simplest way, by making only evaluation of the state variables. In case b) basing on the previous time history of the state variable one of its parameters (e.g. the expected value, or the derivative) is computed, and then its value is estimated. As a result of this estimation an appropriate diagnostic signal is generated. In case c) the diagnostic signal is obtained by checking the qualitative relations between the state variables. In case d) first the residuum value is computed basing on the plant model. Then by evaluating this residuum a diagnostic signal is generated. In the simplest case the residuum may be computed as a difference between the nominal and estimated values of some quality indicator of the diagnosed plant.

4. FAULT DETECTION METHODS FOR POWER ELECTRONICS APPLICATIONS

The tests depicted in Fig.1 lead to the methods of fault detection, which may be split into two basic groups:

- methods that base on the control of the power electronics system parameters,
- methods that make use of the relations occurring between the state variables.

This classification may be presented in a more detailed way by comparing the literature of the subject, as in Fig.2.

In methods basing on the parameter control the symptoms of the faults are detected by analyzing and evaluating the selected parameters. The systems implementing such an approach are usually relatively simple, as they do not need any detailed knowledge of the inverter models. They show also certain disadvantages resulting from limited diagnostic information gained by the knowledge of the values of the signal parameters. This means among others ambiguous reasons of the changes, which makes fixing the relations between the symptoms and the fault difficult.

The control of the limitations consists in making a check whether permissible values or the rate of increase of the state variables are not exceeded, i.e.:

$$x \le x_{\max}\,; \quad x \ge x_{\min}\,; \quad x_k - x_{k-1} \le \Delta x_{\max} \tag{1}$$

Within the fault detection systems there should be distinguished alarm levels and other resulting from the limited reliability of the state variables. Compared with the levels connected with the unreliability the alarm ones show much narrower dead zones. The signal fluctuating around such a level may be the source of a phenomenon known as flickering alarms. In such cases an appropriate hysteresis zone is introduced. The algorithm structure in trend control for simple cases is similar to the structure of an algorithm controlling permissible rate of signal variation:

$$x(t) - x(t-\tau) \le \Delta x_{\max} \tag{2}$$

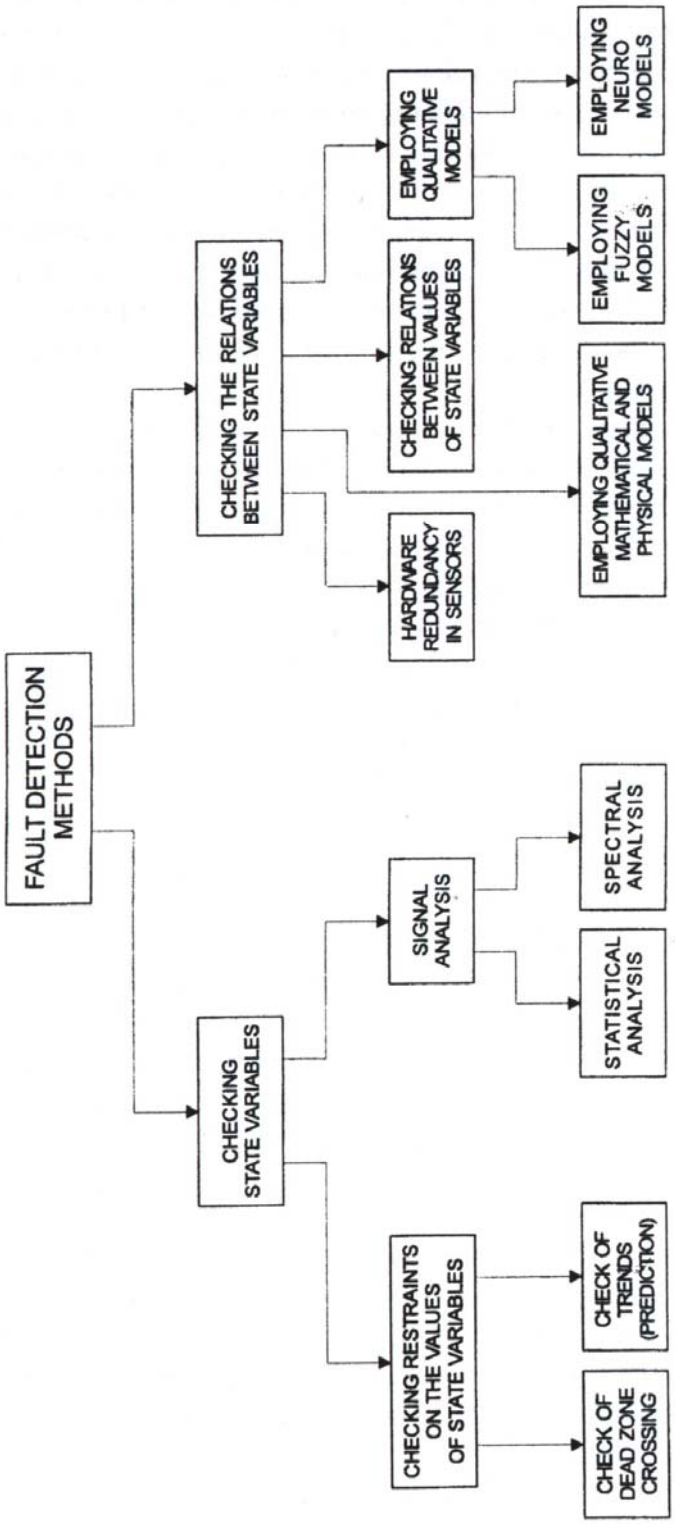

Fig.2. Classification of fault detection methods for applications in power electronics systems.

It should be taken into account with the methods of level crossing check that the time consumed for a fault detection may be considerable in some cases. According to the literature a check of the changes of probabilistic signal parameters gives much chances to detect faults in signal chains. For this purpose measurements of mean values or signal variance are used most frequently. The fault detection system has to calculate those parameters in real time (on line) for a particular time window. Some practical relations and formulas are given in [10]. Sudden, abrupt changes in the expected value and variance may reflect either an occurrence of a fault or disturbance, or indicate inappropriate control of the inverter. It must be stated here that these parameters check is well justified in case of a normal distribution of the state variables' changes in the steady state.

For signal spectral analysis time sets are used, which are obtained through signal sampling. It is assumed that the observed train is an accomplishment of a stationary discrete process, which meets the hypothesis of ergodicism. This means steadiness of the expected value and that autocorrelation function depends exclusively on the time shift of the train components. The ergodic condition is met when the averaging of a random process over the accomplishment set gives similar results to time averaging of one of its possible accomplishments. Time sets are described in the time domain by autocorrelation function. By transforming it with one of the fast orthogonal transforms the power spectral density function may be obtained.

In normal (stationary) operation of the inverter each individual state variable is characterized by definite forms of the autocorrelation and power spectral density functions. The occurrence of faults causes these characteristics to change. If it happens to fix the influence of the individual faults on the shape of the autocorrelation or power spectral density functions then fault detection and isolation becomes feasible. The present authors are of the opinion that just this methodology is the most promising in the diagnostic of power electronics equipment. For the methods using relations between the state variables it is needed to know the quantitative or qualitative models of the power electronics equipment. A check of these relations made on-line makes it possible to detect faults in all of the components of the diagnosed plant. Then both linear and non-linear state equations, various type state observers, Kalmann filters etc. are employed for the residuum generation. Analogous fault detection methods have been developed in recent years, in which neural and fuzzy models are used, fuzzy neural nets including, which is particularly applicable for non-linear plants and also in cases when making analytical models poses too much difficulty or is impossible at all [2].

From the practical point of view particular attention should be paid to the hardware redundancy method. Employing two or more devices executing the same tasks makes it possible to compare their operation and to detect faults if they occur. A measure of discrepancy is then the residuum computed as the difference between the appropriate signal parameters from the both devices. This hardware redundancy method is quite simple and effective, however expensive. It is mainly employed in diagnostics of the measurement paths [1]. Applying mathematical models for computing some state variable values instead of redundant measuring devices is known as the analytical redundancy method [2]. The residuum is obtained then as the result of a comparison made on the model output and the actual measured signal. Within this group of fault detection methods a detection using state observers or Kalmann filters is to be mentioned, as well as detection with identification in real time [3].

Relations between the time sets of the selected state variables may also be used for fault detection. Assuming their stationary and ergodic nature one can fix their cross-correlation and covariance functions.

The breakdowns of single input-output dynamic plants, that are described by non-linear differential equations, can be detected by estimation of the residual values computed from these equations. The physical equations should comprise the influence of the fault upon the output. Then the residual generation can be a detection method, but only when the model accuracy is sufficient enough.

5. MONITORING

An important obstacle in monitoring power electronics equipment arises when no special test forcing may be applied. It results from the working conditions that only operating signals may be used for test purposes and the diagnosis can be formulated including propagation times of the fault symptoms.

Block scheme of the inverter state monitoring process may be depicted as in Fig.3. In this case the monitoring of the inverter comprises the following:

- fault detection performed repeatedly;
- fault isolation;
- fault identification;
- detection of a probable recovery, i.e. return to the state of normal operation (known in the literature as a state of usability);
- optional visualization and storage of the diagnoses;
- optional modification of the file storing the faults that have been considered in the inferring process.

Basically the following two independent processes may be distinguished in the described monitoring system, that are accomplished in real time in parallel by the different tasks of a multitasking operating system:

- repeatable execution of the fault detection tests;
- all the other activities mentioned above, accomplishing the monitoring process.

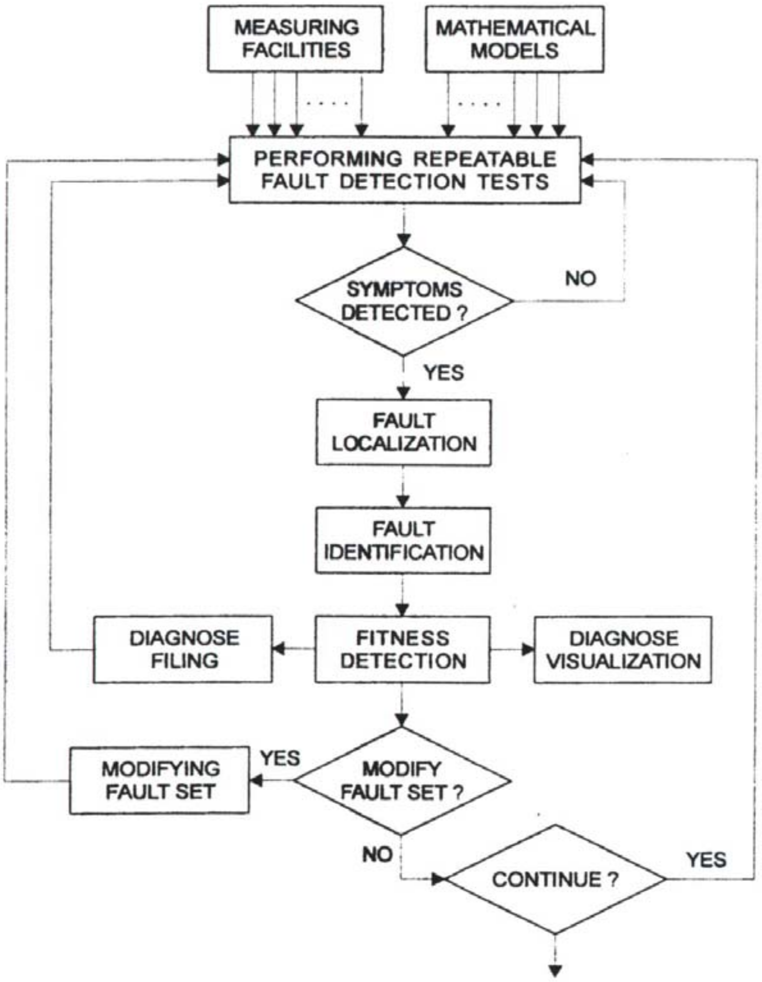

Fig.3. Process of monitoring the state of the inverter.

In order to perform the A/D conversion while maintaining the required accuracy usually it is necessary to employ some additional circuitry, like analog filters, multiplexers or AD converters. The processed digital signals are supposed to contain the necessary information and should be recoverable. The task of the analog filters first of all is to limit the signal spectrum to meet the requirements of the sampling theorem. The multiplexers are intended to enable multiple signal processing by means of a single converter. The sampling frequency must be chosen accordingly so to fit the signal's components carrying essential information. The high frequency noise content of the signals must be suppressed before sampling in order to restrain its influence upon the low frequency useful components.

A power electronics inverter is a dynamic system, thus it takes some time from the moment the fault occurs until the first measurable symptoms appear, which depends on the appropriate time constants. The tests these authors carried out for an inverter show, that the same fault can be detected with different delay times depending on the kind of the test signal. Therefore we claim that neglecting the dynamics of the symptom's growth within the inverter may result in generation of false diagnoses. Time delays of a symptom emerging depend also on the kind of the fault:

- disastrous faults produce symptoms at minor delays,
- slowly growing faults, e.g. those related to the wear of the system's elements, produce symptoms most often very late, not to mention their less distinct character.

The times the symptoms emerge depend also on additional factors, like:

- how broad the dead (insensitivity) zone is – the narrower the interval of allowable residual values is, the shorter is the time of detection, however, at the same time the greater is the threat of false alerts;
- the criteria, according to which the diagnostic signals are evaluated – – a threshold criterion produces effect differing considerably from that of a fuzzy one;
- working point of the inverter;
- numerical parameters of the employed detection algorithm and the computer system used.

An exact analytical estimation of the delays in the symptoms' emerging is impossible in the opinion of the present authors, since in case of power electronics equipment there are highly inaccurate models encountered, that do not cover fully the physics of the phenomena, and because no knowledge is available about the dynamics of a fault emerging. In practice basing on the knowledge of the inverter's dynamics and detection algorithms one can try to estimate the times of the symptoms by indicating their minimum and maximum values, after having carried out appropriate simulations.

6. FORMALIZATION

We define the set of all feasible faults H for each diagnosed plant:

$$H = \{ h_k , k = 1, 2, 3, ...K \} \tag{3}$$

To each element h_k of the fault set F there is a corresponding state $x(h_k)$ defined as:

$$x(h_k) = \begin{Bmatrix} 0 \text{ - no fault} \\ 1 \text{ - fault present} \end{Bmatrix} \tag{4}$$

The state of the inverter is defined by the states of all its components. Each of these components may take one of many possible corresponding states, among which we can distinguish states of full fitness, partial fitness and state of breakdown. The number of all possible states of the inverter is a product of the state subsets' populations for all its components.

We assume that the state of the inverter is defined by the set of the existing faults, since by the occurrences of faults arise states of partial fitness and breakdown. If in the diagnosing process all the faults are isolated and their extents identified, then we can say that the state of the plant has been fixed.

The state of the inverter is thus fixed by the states of all its faults belonging to the set H.

$$x = \{x(h_1), x(h_2), x(h_3), ..., x(h_k)\} \tag{5}$$

The set X of all the states x_i of the inverter may be expressed by the relation:

$$X = \{x_i : i = 0, 1, 2, ..., I\}, \quad I = 2^K \tag{6}$$

It may be expressed as a sum of the state subsets with the fault number m, where $m = 0, 1, ..., K$.

$$X = \bigcup_{m=0}^{K} X_{(m)} \tag{7}$$

where:

$$X_{(m)} = \left\{ x_i \in X\, ; \sum_{k=1}^{K} x(h_k) = m \right\} \tag{8}$$

is a subset of the inverter states, in which there are m faults present simultaneously.

The state x_i may be described explicitly in terms of the set $H(1)$ of faults occurring in it. Thus to each of the states x_i may be attached a subset $H(1)$ such, that:

$$H(1)_1 = \{ h_k \in \mathrm{H}\, ; x(h_k)_i = 1 \} \tag{9}$$

where:

$x(h_k)_i$ is the state of fault h_k within the state of the inverter x_i.

The knowledge of the time history of both analog and digital signals makes it possible to evaluate the dynamics of the energy conversion process. For the fault isolation we use some sets of the diagnostic tests that output diagnostic signals. We denote the set of the tests:

$$D = \{ d_j : j = 1, 2, 3, ..., \mathrm{I} \} \tag{10}$$

As a result of accomplishing all the tests of the set D we obtain a set of the diagnostic signals S:

$$S = \{ s_j ; j = 1, 2, 3, ..., \mathrm{I} \} \tag{11}$$

The algorithms of the tests are based on different methods of detection, shown above in Fig.1.

Fault detection is a process of projection of the state variables space X onto the space of the diagnostic signals S:

$$X \in R^N \Rightarrow S \in R^J \tag{12}$$

We define the relation Q_{xs} upon the Cartesian product of the sets S and X:

$$Q_{xs} \subset X \times S \tag{13}$$

The relation $x_i \, Q_{xs} \, s_j$ will mean that the value of a state variable x_i will be used by the test d_j to produce diagnostic signal S_j.

Graph G_{xs} may be written in the form:

$$G_{xs} = < X, S, Q_{xs} > \tag{14}$$

The set of its apexes consists of the elements of the sets X and S and has its sides described by means of the relation Q_{xs} as defined by (13).

7. SIMULATION OF THE SYSTEM OPERATION

7.1. The investigated systems

As an example the following typical 6-pulse controlled bridge rectifier was adopted, shown in Fig.4.

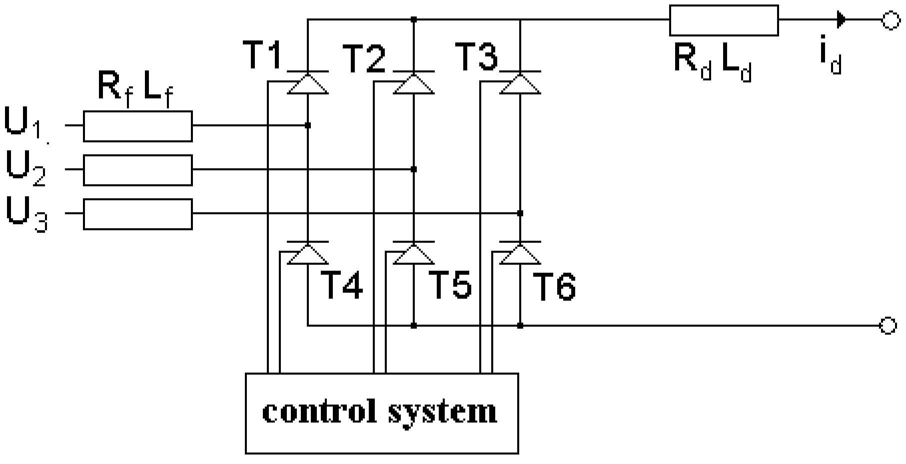

Fig.4. Arrangement of the rectifier.

Operation of the rectifier was analyzed for the two typical loads:

a) with classical RL circuit;
b) an external excitation DC motor.

In case a) the motor was fed from a symmetric tri-phase mains at the rated voltage of 220 V. The initial load parameters were: $R = 5\Omega$; $L = 0{,}25$ H. The rectifier was controlled in a simple arrangement with a single PI controller acting as a current regulator.

However, a classic motor control system with two PI controllers (speed $R\omega$ and current RI) shown in Fig.5, was employed for case b).

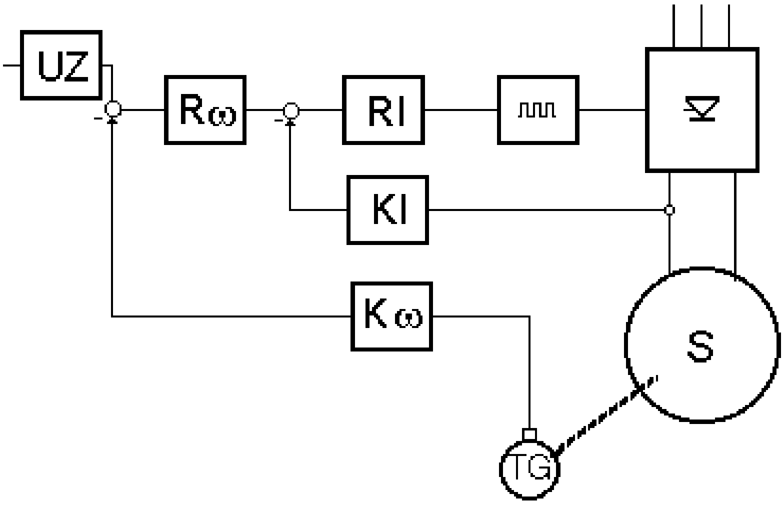

Fig.5. Block diagram of the DC motor control.

The external excitation DC motor used in the investigation was rated as follows:

$P_N = 364$ kW	$U_N = 400$ V	$I_N = 960$ A
$R = 13{,}7\ \Omega$	$L = 0{,}57$ H	$n_N = 1135$ rpm
$J = 15\ \mathrm{kgm}^2$		

7.2. Description of the investigations

7.2.1. The RL load

The model of the inverter used for simulation includes its variable structure depending on the switching on and off of the individual thyristors (valves).

A schematic circuit for the case when thyristors T1 and T2 are conducting is shown in Fig.6.

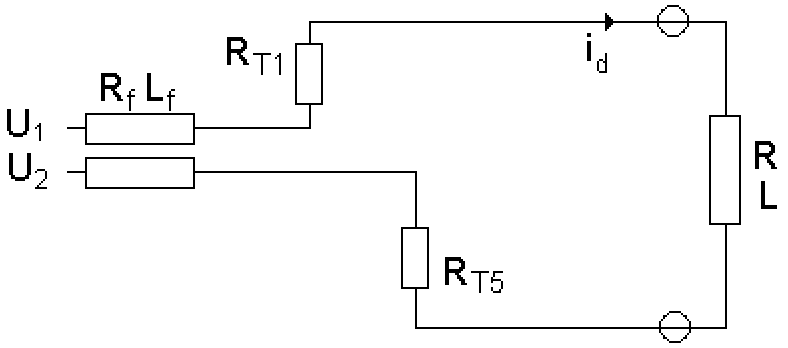

Fig.6. Schematic circuit for conducting thyristors T1 and T5.

The symbols used in the figure have the following meaning:

R_f, L_f – resistance and inductance of the mains supply and rectifier transformer;
R, L – load resistance and inductance of the DC link;
R_T – resistance of the conducting thyristors (resistance in the reverse direction was assumed infinite),
U_1, U_2, U_3 – mains supply phase voltages.

Obviously the schematic diagram is analogical in the other cases of conduction for the consecutive thyristors.

The circuit has a slightly different structure during commutation of individual valves, while the angle of commutation μ for the investigated bridge arrangement may be obtained from the following relation [12]:

$$\mu = \arccos\left[\cos\alpha - \frac{\omega \mathrm{L_k} \cdot i_d}{U_m \cdot \sin\left(\frac{\pi}{6}\right)}\right] - \alpha \tag{15}$$

where:

α – delay angle in the thyristor switching on;
L_k – inductance of the commutation circuit;
U_m – amplitude of the line voltage;
I_d – rectified current.

The schematic diagram of such an arrangement when commutation is occuring between thyristors T5 and T6 is shown in Fig.7.

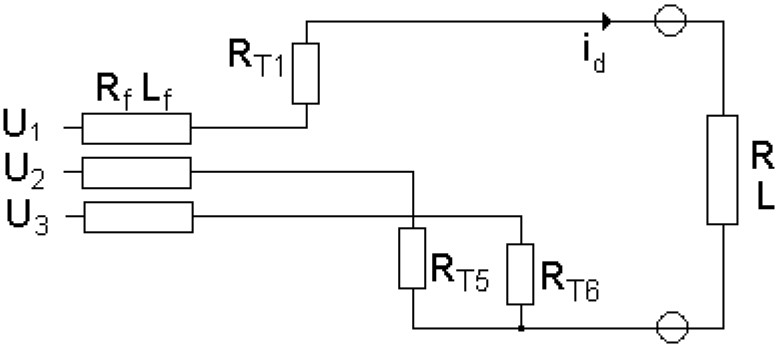

Fig.7. Schematic circuit at commutation of T5 and T6.

In this paper we consider only the above case of simple commutation, when no complex commutation occurs even under fault conditions.

7.2.2. External excitation DC motor load

A classical model of external excitation DC motor controlled from the rotor side via a static inverter and described by the following classic equations was considered:

$$\overset{\bullet}{i} = -\frac{\mathrm{R}}{\mathrm{L}}\cdot i - \frac{c_e\Psi}{\mathrm{L}}\cdot \omega + \frac{\mathrm{U}}{\mathrm{L}} \tag{16}$$

$$M_{el} = c_m \cdot \Psi \cdot i \tag{17}$$

$$\overset{\bullet}{\omega}1 = \frac{(M_{el} - M_o)}{J} \tag{18}$$

where:

I – rotor current (I_d)
U – supply voltage
R, L – rotor resistance and inductance
ω_1 – rotor speed
Ψ – motor flux
c_e, c_m – motor constants
M_{el}, M_o– motor torques and load torque.

The model was complemented with the control system equations corresponding to Fig.5.

7.3. Simulation of the rectifier

The goal of this work was to analyze the inverter – load arrangement in faulty states and to state possible ways to diagnose appearing faults and choose the elements of the monitoring nodes subset. Usually this subset is composed of the input and output variables of the subsystem, thus in this case there will be:

- voltages and currents of the mains supply,
- the inverter output voltages and currents.

For the case of intermediate frequency converter additionally the DC link voltages and currents may be used.

7.3.1. RL load

The following operation cycle of the rectifier was analyzed: initial operation with the load as given before ($R=5\Omega$, $L=0,25$ H) while setting the values corresponding to the output current of 35 A. Then at $t = 0,24$ s appear individual types of faults in the system. These faults were relatively small, therefore the usual protections do not operate yet, while classical alerting systems most probably would not signal any unusual condition. Anyway it is of great importance to recognize and diagnose the fault, since this permits to prevent its further evolution, which could lead to a major damage and considerable losses. The following faults were selected:

I. fault in the load circuit of the inverter (partial shortcut in the load);
II. fault in the supply part of the rectifier, manifested as no voltage in phase I;
III. damage in thyristor T1, in the form of increased resistance within the interval of conduction;
IV. faulty control of the thyristors, manifested as a small additional delay in switching on the T1.

So these cases may be classified as faults before the inverter, after and within it, as well as in the control of the inverter. Additionally the effect of increased extent of the thyristor damage (which manifests by further increase of the resistance within the conduction period) on the behavior of individual state variables.

The obtained current vs. time waveforms are presented in Figs.8 – 11. They are:

- the rectifier output current when the in I – IV faults described above are present – Figs.8 – 11;
- the rectifier output current obtained with different extent of the fault in a thyristor, Figs.12 – 14.

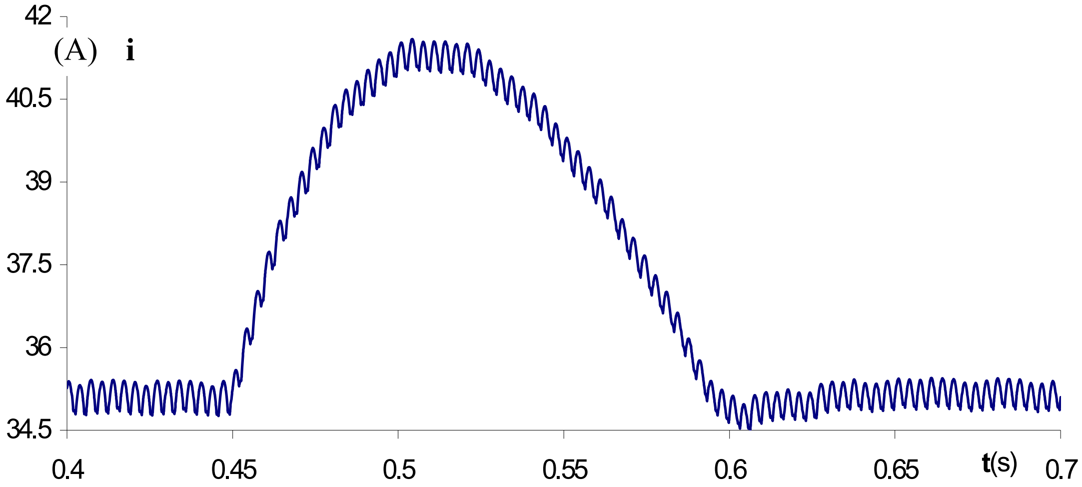

Fig.8. Rectifier current vs. time for a fault in the load.

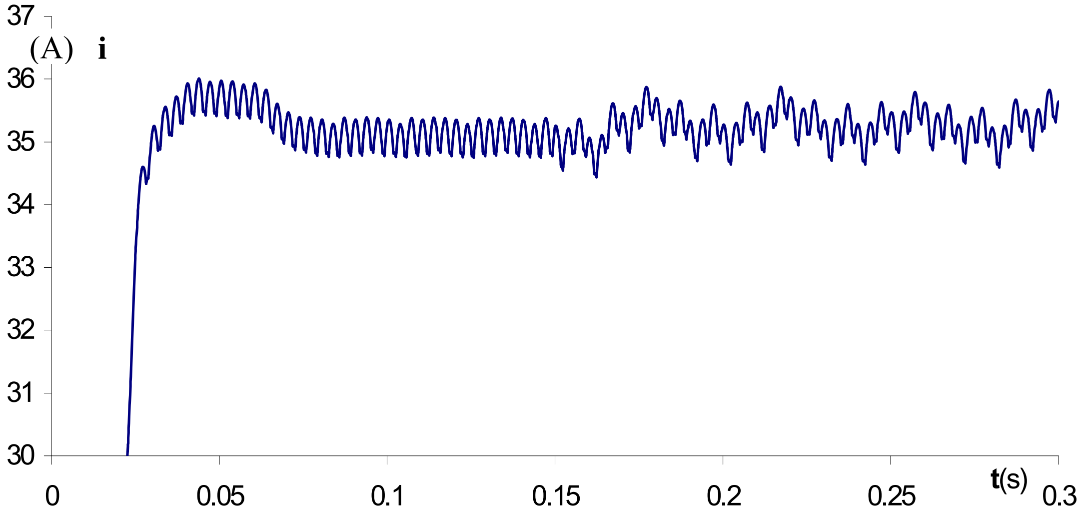

Fig.9. Current vs. time for faulty mains supply.

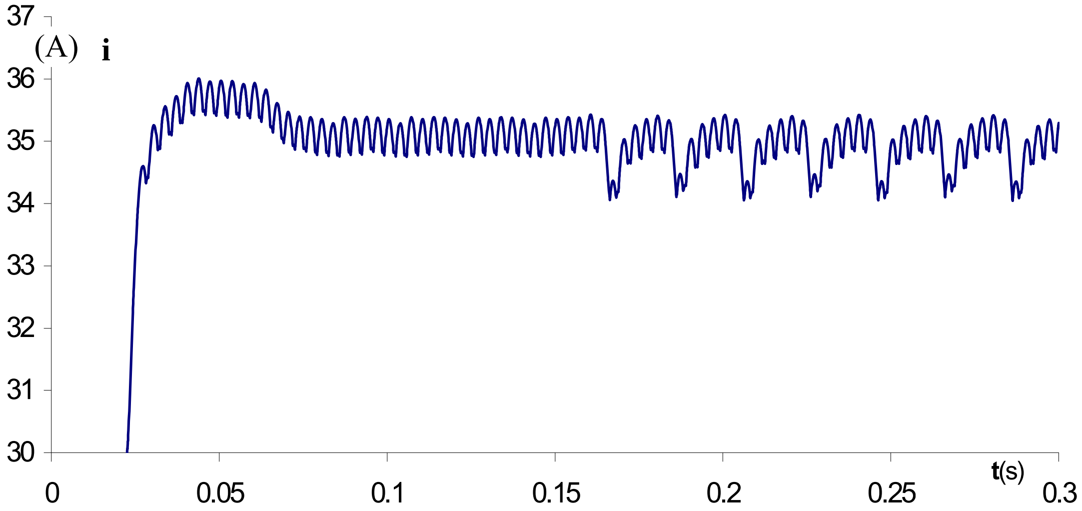

Fig.10. Current vs. time for faulty control.

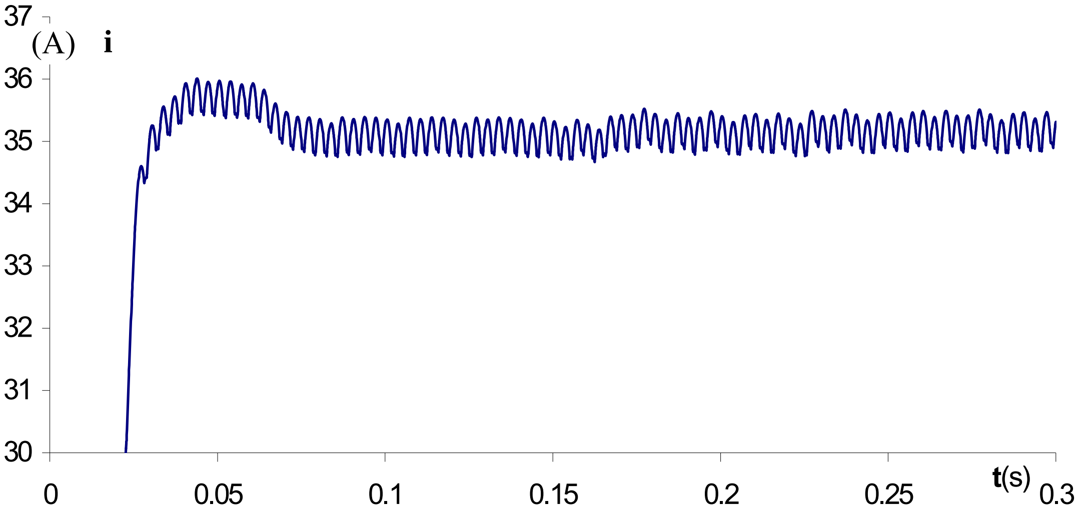

Fig.11. Current vs. time for faulty thyristor – minor fault.

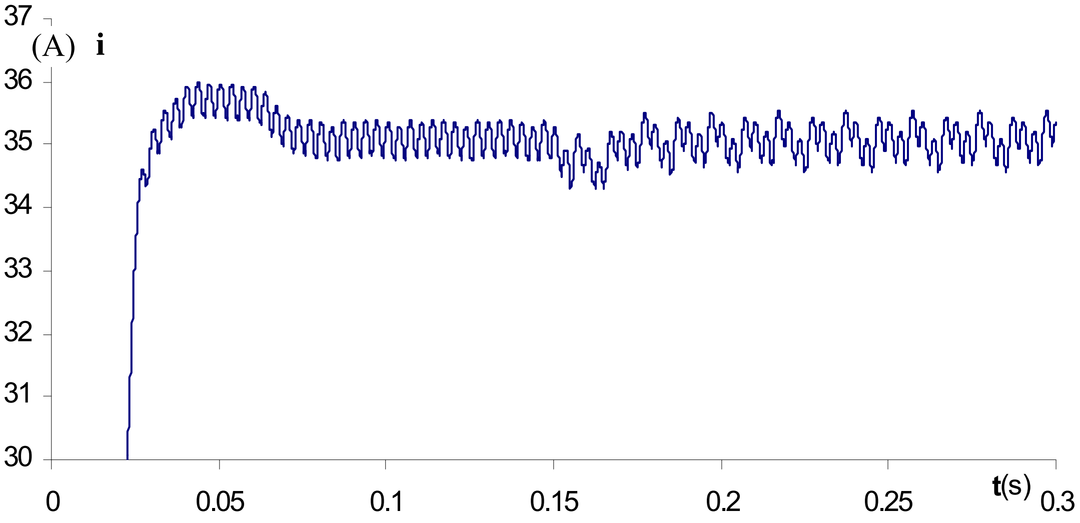

Fig.12. Current vs. time for faulty thyristor – 2nd degree fault.

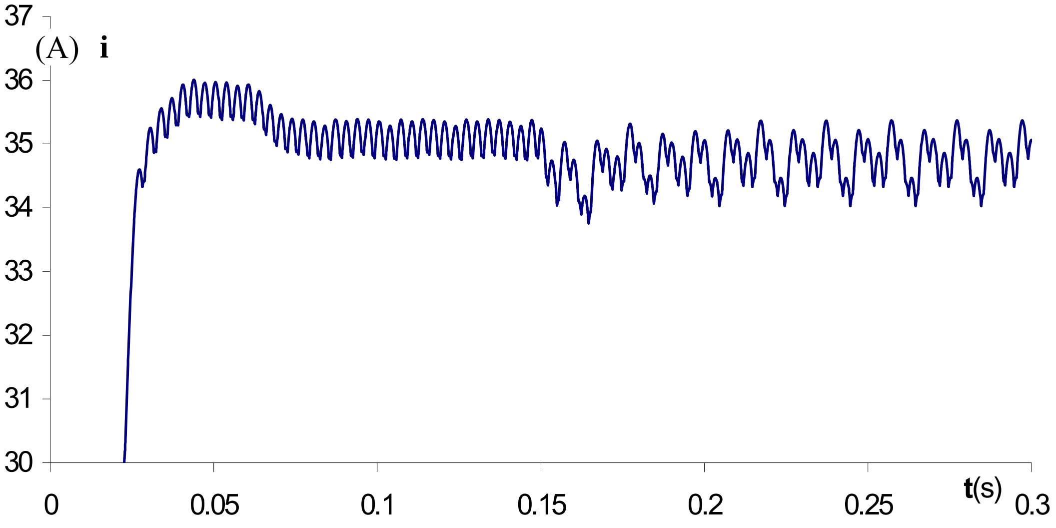

Fig.13. Current vs. time for major fault in the thyristor – 3rd degree fault.

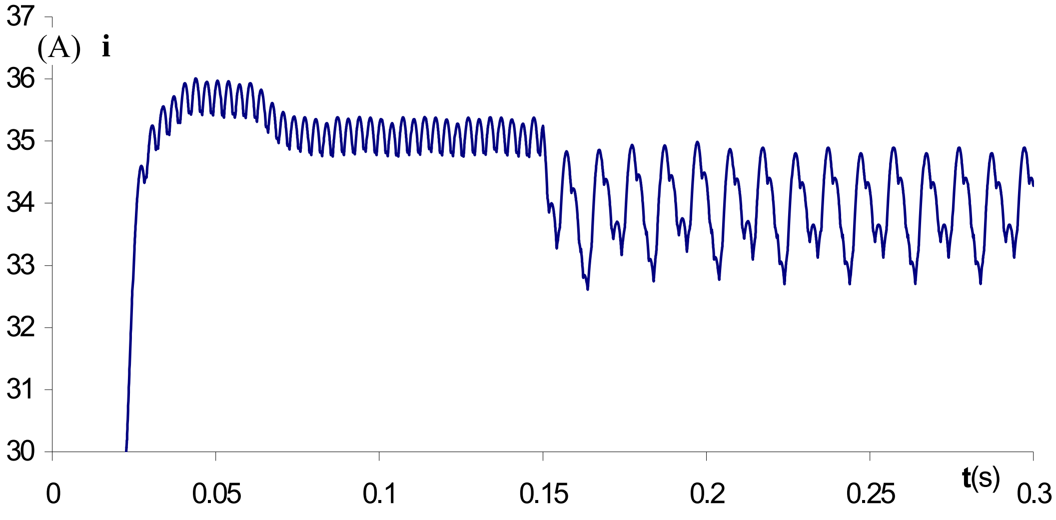

Fig.14. Current vs. time for severe fault in the thyristor – 4th degree fault.

The characteristic values of the rectifier's output current in each of the operation points are shown in Table 1. They are: mean value, mean oscillation amplitude, and maximum oscillation amplitude, and all they concern the steady state of operation.

TABLE 1

No	Operating condition	Average value (A)	Average amplitude of oscillation (A)	Maximum amplitude (A)
1	no fault	35,070	0,216	0,394
2	faulty load	35,169	0,164	0,327
3	faulty supply	35,271	0,212	0,677
4	faulty thyristor	35,166	0,183	0,401
5	faulty control	34,898	0,293	0,845

Analysing the above waveforms and the figures in Table 1 one can state that minor faults in the network result in hardly noticeable changes in the state variables in time domain (rectified current and voltage), usually fitting well within the range of measurement errors. Basically this influence may be observed only by thoroughly analysing the nature of individual time waveforms, however these changes can be barely noticeable (e.g. with the faulty thyristor – Fig.11.). Very hard, or almost impossible is more detailed definition of the fault extent (Figs. 12, 13, 14). Only further growth of the fault produces more noticeable changes in the values and nature of the current (Fig.14). Thus it becomes an important task to find an efficient method for detection of fault occurrences as well as to recognize their extent and nature.

The above conclusions suggest to carry on the qualitative analysis of the selected and measurable signals of the rectifier network with the goal of diagnosing.

7.3.2. External excitation DC motor as load

Also in this case we simulated the operation with no fault condition and with different faults like in the case of the RL loaded rectifier.

We continued to simulate the operation at the same angular speed ($\omega = = 94{,}735$ rad/s) and individual fault occurences at $t = 3$ sec. They were the following:

- faulty supply,
- faulty T1 thyristor in the rectifier,
- faulty motor,
- faulty rectifier control.

The current waveforms obtained for individual faults (corresponding to the above description) are presented in Figs.15 –18.

The characteristic rectifier output current values for individual working conditions are shown in Table 2. These are the same quantities as for the case of the RL load – section 7.3.1. The corresponding values of the angular velocity of the rotor are presented in Table 3.

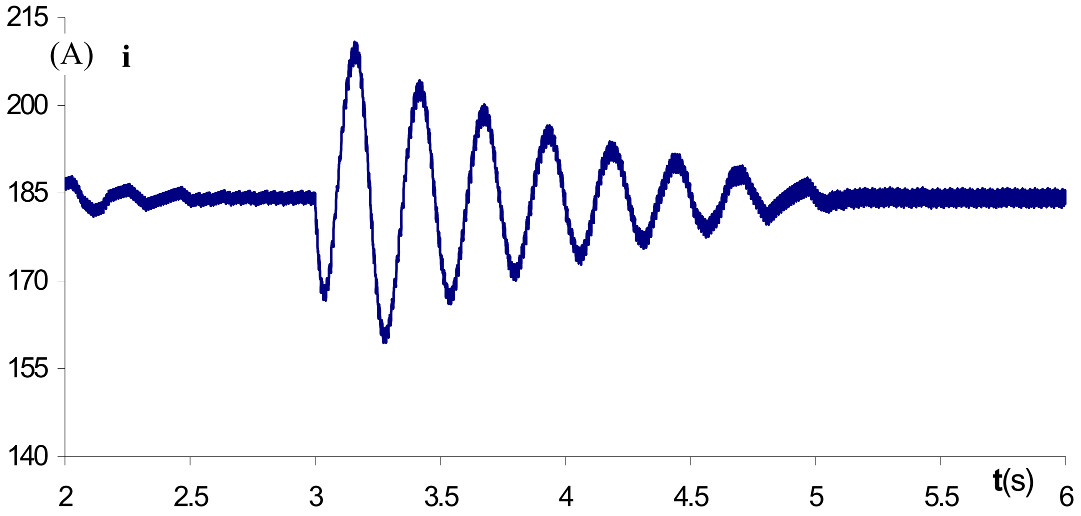

Fig.15. Motor current waveform for faulty thyristor.

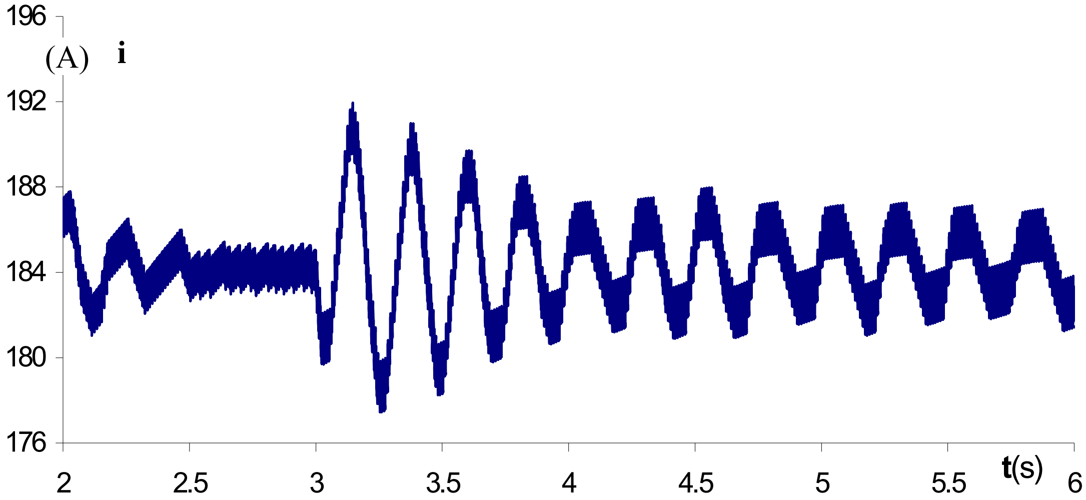

Fig.16. Current waveform for faulty mains.

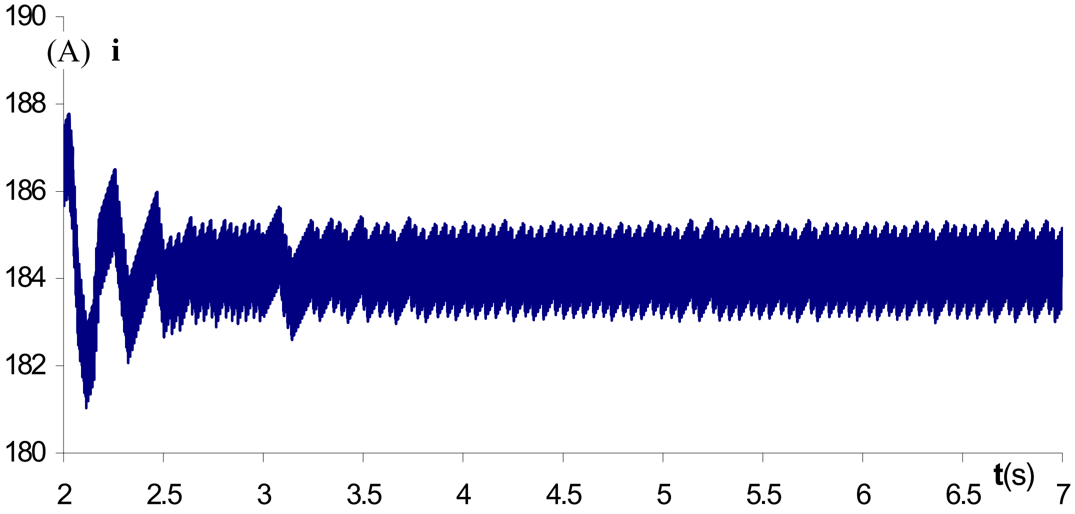

Fig.17. Current waveform for faulty motor.

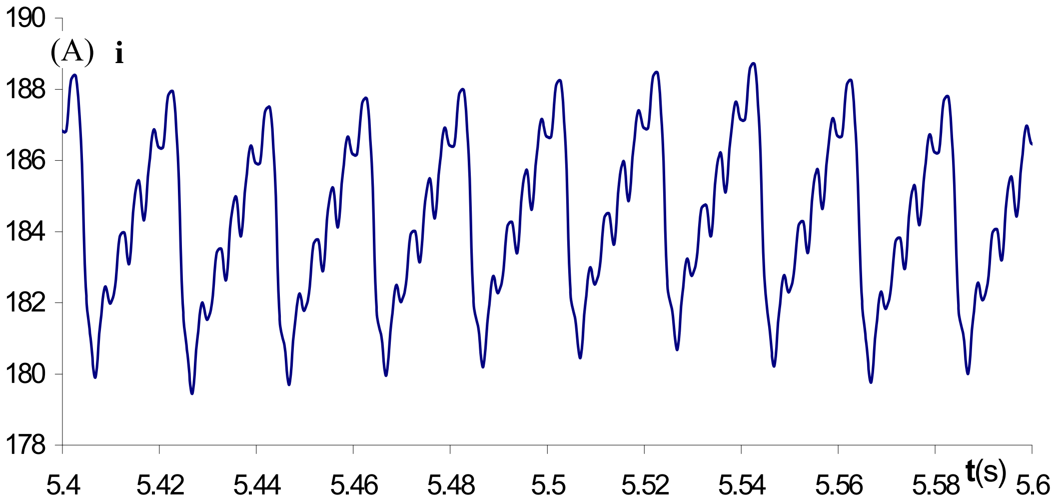

Fig.18. Current waveform for faulty control.

TABLE 2

No	Operating condition	Average value (A)	Average amplitude of oscillation (A)	Maximum amplitude (A)
1	no fault	184,317	0,586	1,69
2	faulty supply	184,386	1,181	3,34
3	faulty thyristor	184,339	0,898	1,879
4	faulty motor	184,343	0,526	1,33
5	faulty control	184,341	2,001	4,893

TABLE 3

No	Operating condition	Average value (rad/s)	Average amplitude of oscillation (rad/s)	Maximum amplitude (rad/s)
1	no fault	94,737	0,0039	0,018
2	faulty supply	94,738	0,0097	0,020
3	faulty thyristor	94,737	0,0013	0,013
4	faulty motor	94,737	0,0004	0,002
5	faulty control	94,737	0,002	0,006

Also with motor load the influence of the individual minor faults on the individual state variables (particularly on angular velocity, which is stabilised by the control circuit) is practically negligible in steady states. Barely noticeable current oscillation was observed with a fault in the cathode choking coil, whereas the deviation of the current average value was also minute and amounted to approximately 0.621 A. A little bit more distinguishable effect appears only at transients, but since it lasts approximately 1 – 2 seconds its observation is also difficult.

Also in this case the analysis of the waveforms allows to distinguish some differences for individual kinds of faults, although again estimation of the sort and extent of the fault is very difficult, if not to say impossible.

So a conclusion can be made that estimation of the nature and extent of a fault basing on the analysis of individual state variables time histories is insufficient and may only be considered merely a preliminary evaluation. However, a more accurate evaluation may be searched for among more sophisticated methods, like e.g. qualitative analysis of the selected measurable signals.

8. QUALITATIVE SIGNAL ANALYSIS OF THE INVESTIGATED INVERTER USING HAAR TRANSFORM

To identify faults in a rectifier network we employed in this paper a method based on the theory of orthogonal evolutions. A fast FHT transform algorithm, based on Haar matrix factorization [9, 19] was selected. The employed approach made it possible to identify the characteristics of the diagnosed system in different working conditions. With fast transforms the fault isolation may be performed in real time.

There were some assumptions adopted in order to enable the analysis, concerning properties of the time sets obtained from simulation. The following constraints were imposed on selected signals:

- the length of the data record was limited to a natural power of two;
- the range of variability for the recorded values was restrained;
- the data were sampled and recorded within selected time intervals;
- the data were quantized with limited accuracy;
- the sampling period was constant.

It was also assumed in the considerations that the processed signals were generated by stationary and/or ergodic processes. That meant that spectral characteristics of the waveform in question were constant (fixed) with time axis translation.

The fact that the signals are non-stationary results from the variations in time of the properties of both the power electronics system and its load (RL network or motor). The non-stationary feature may also result from the changes of working conditions of the drive, so may be the consequence of the disturbances occurring. The rate at which the parameters change their values is then essential. It is assumed in this paper that these changes are relatively slow and negligible within the time span of a single measurement window, which in practice makes reasonable the assumption the waveforms are stationary within the considered time intervals.

The algorithms of Haar fast transforms, that were used to obtain spectral characteristics of individual signals are presented in [9]. Analyzed were the time characteristics of the inverter output currents and voltages. As a result of numerical experiments the signal Haar spectra were obtained for the following cases:

- RL load – sec. 7.3.1,
- An external excitation DC motor acting as a load – sec. 7.3.2.

The following figures show spectral characteristics when either faults are present or not for the following signals:

For 7.3.1:

- Output rectifier current, operation with no fault – Fig.19.

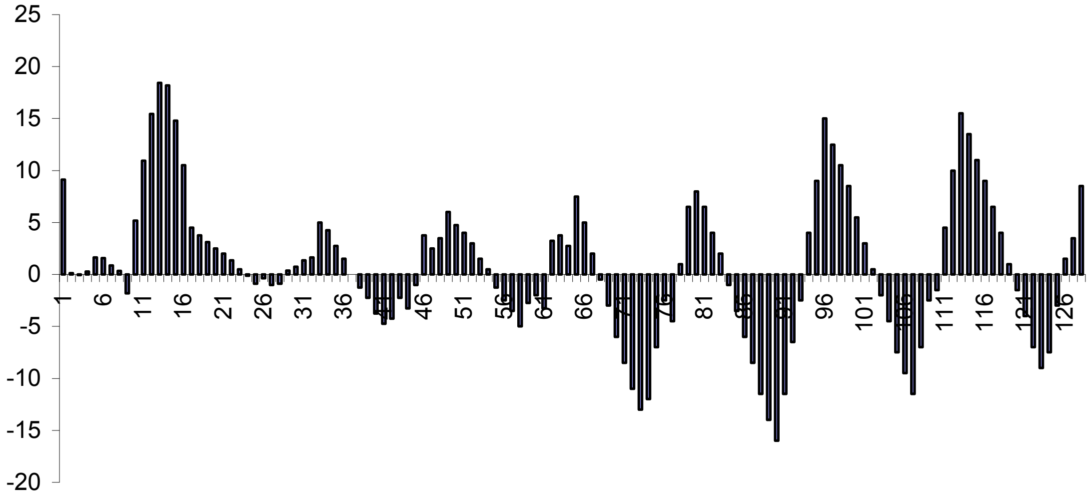

Fig.19. Haar spectrum for no fault operation of the RL loaded rectifier.

- Currents for different fault types and extents, according to the description in section 5 – Figures 20 – 26.

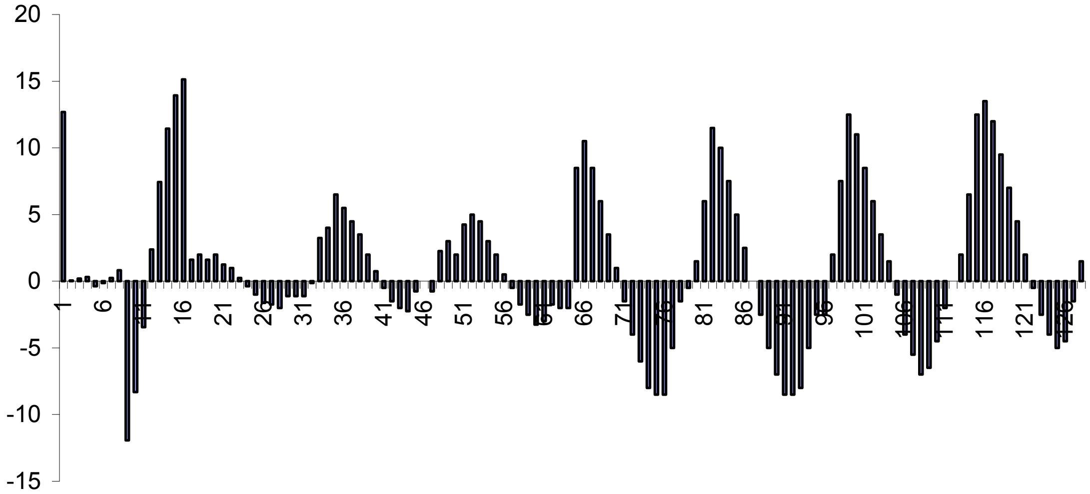

Fig.20. Current Haar spectrum for faulty load.

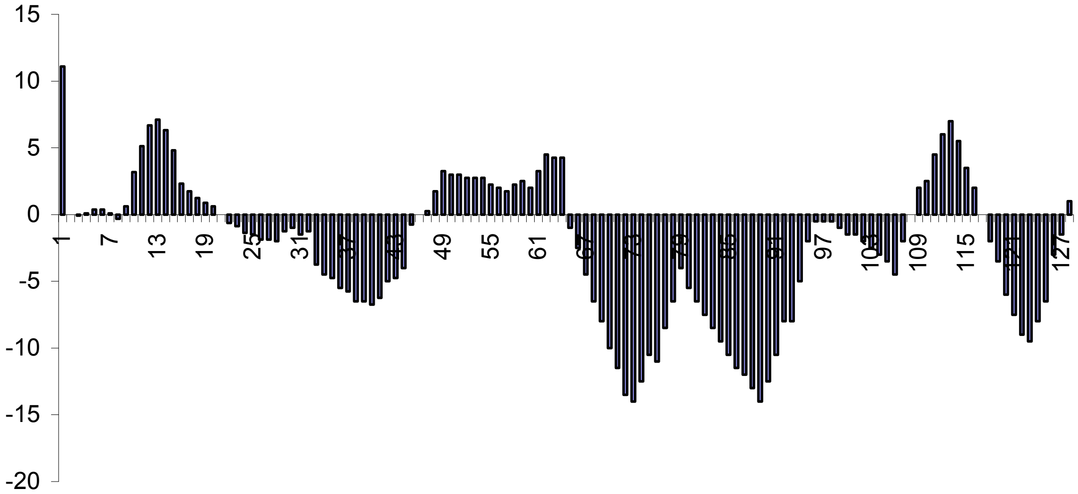

Fig.21. Current Haar spectrum for faulty mains.

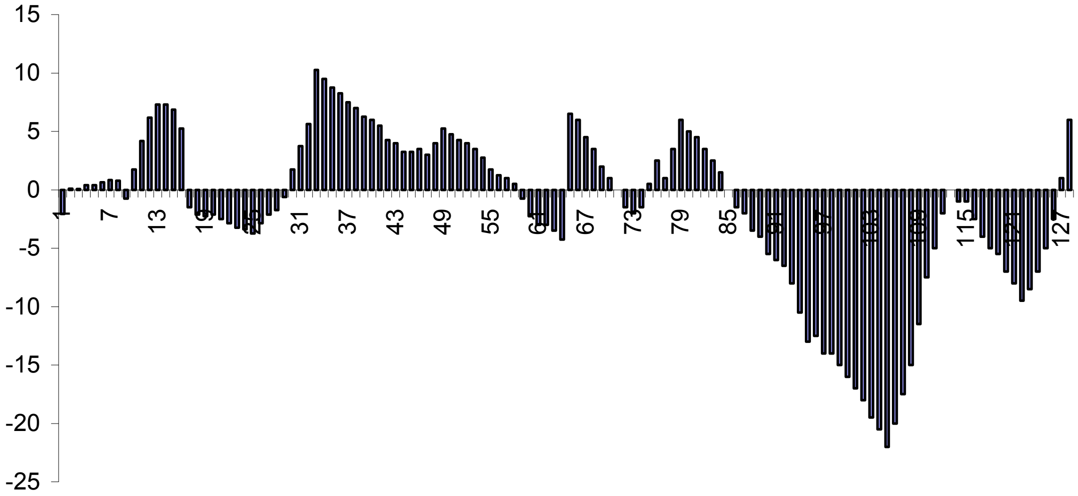

Fig.22. Current Haar spectrum for faulty control.

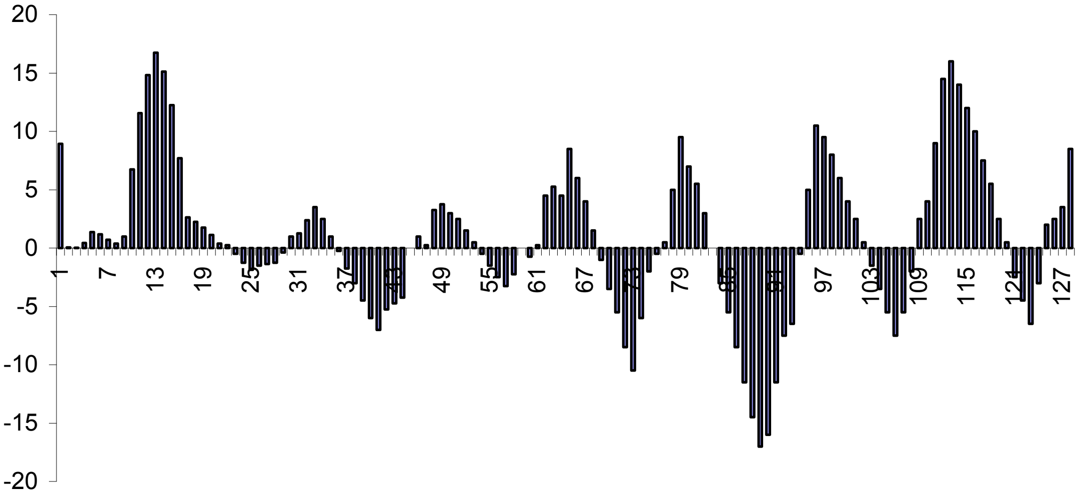

Fig.23. Current Haar spectrum for a minor fault in the thyristor.

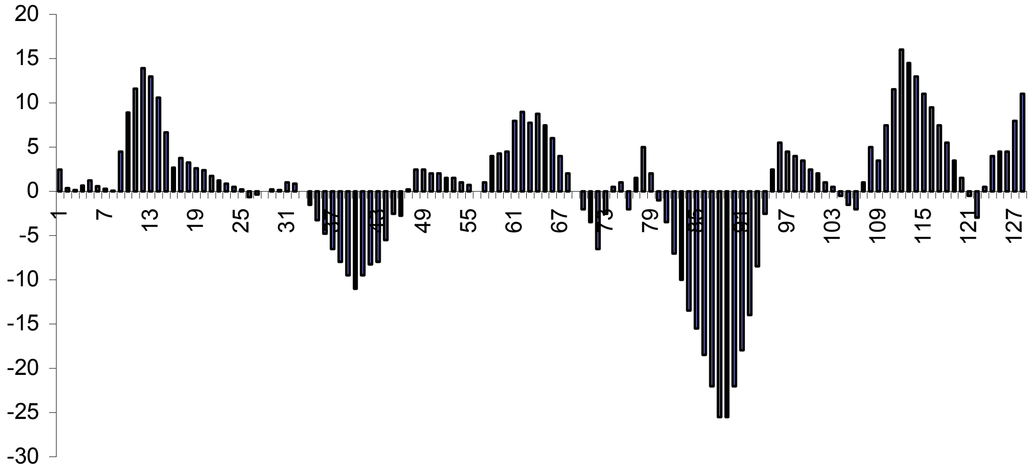

Fig.24. Current Haar spectrum for a faulty thyristor – 2nd degree severity fault.

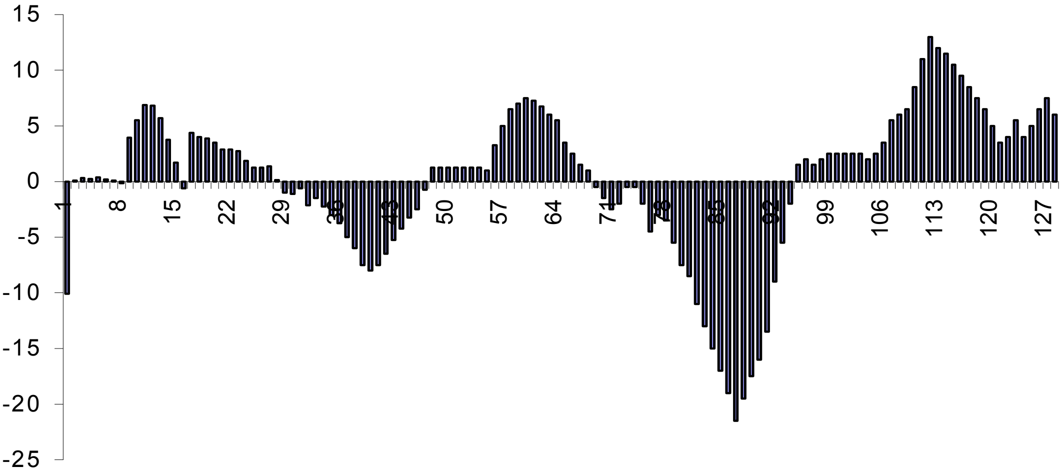

Fig.25. Current Haar spectrum for a faulty thyristor – 3rd degree severity fault.

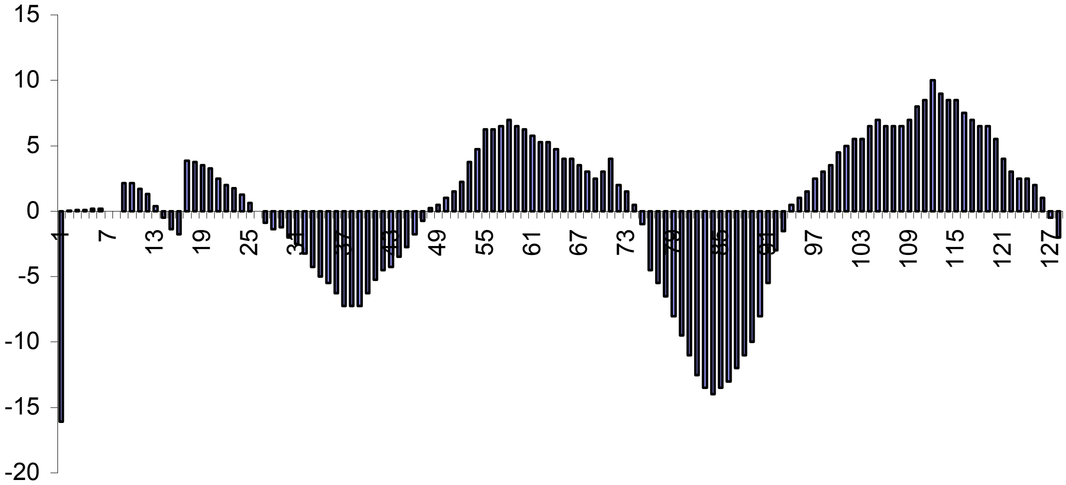

Fig.26. Current Haar spectrum for a faulty thyristor – 4th degree severity fault.

For sect. 7.3.2.

- Current, no fault operation – Fig. 27.

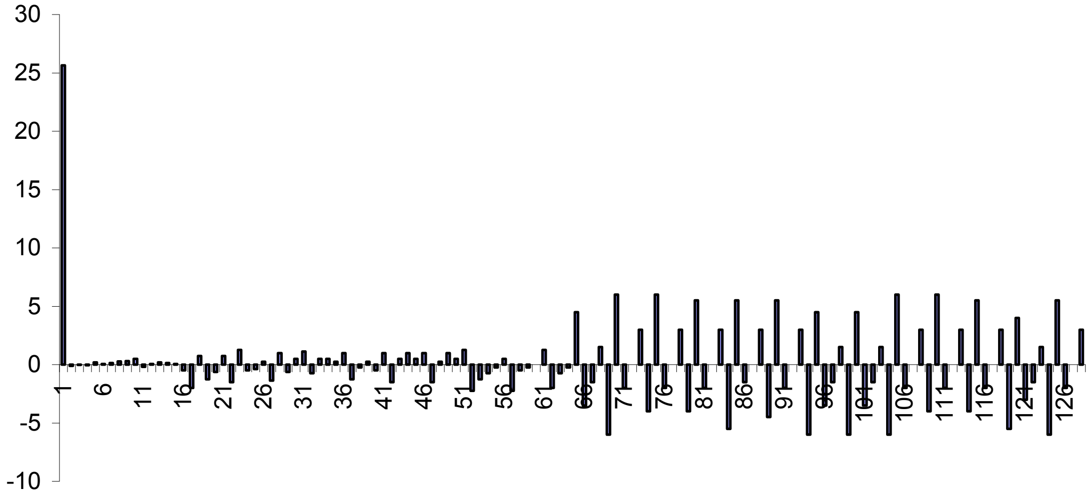

Fig.27. Current Haar spectrum – no fault (motor load).

- Currents, for individual faults –Figs.28 – 31, according to those described in section 7.3.2.no fault operation – Fig.27.

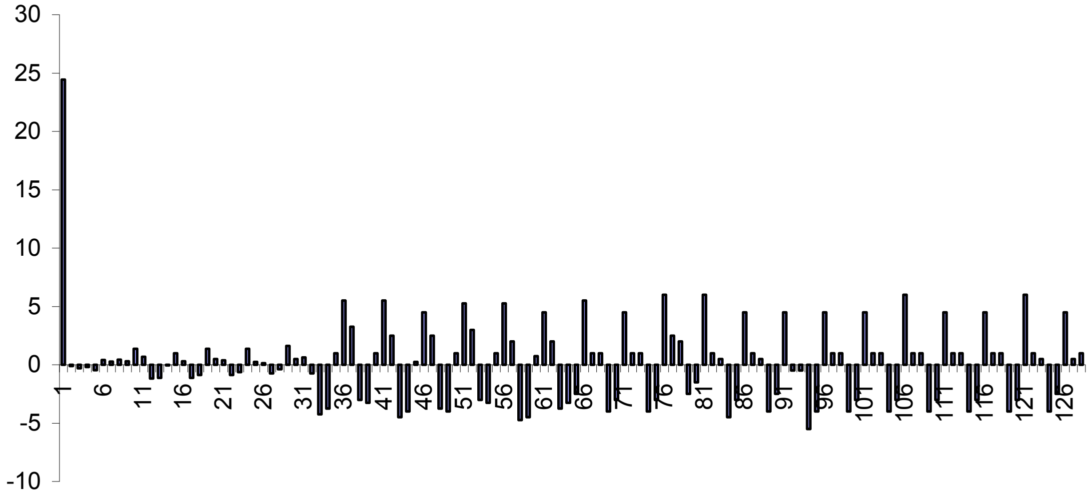

Fig.28. Current Haar spectrum for a faulty thyristor.

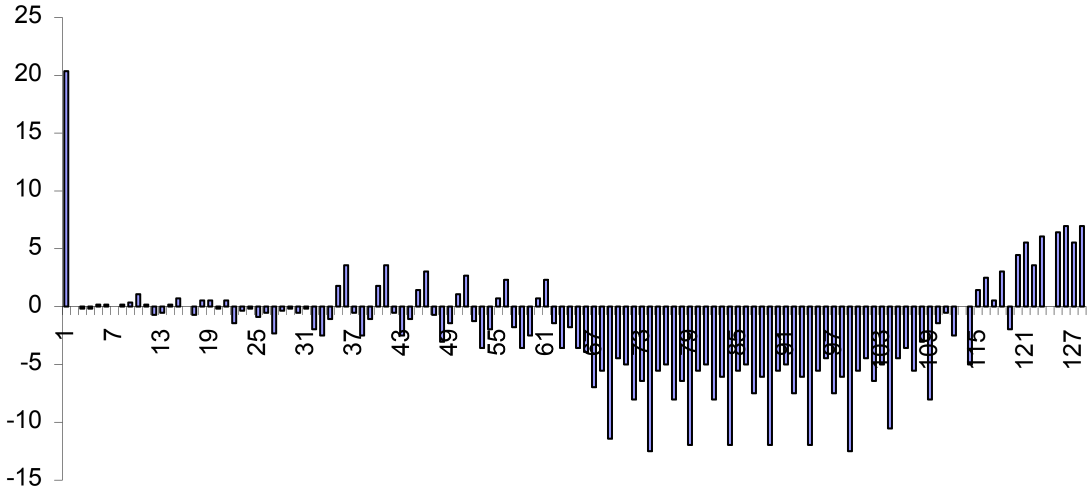

Fig.29. Current Haar spectrum for faulty mains.

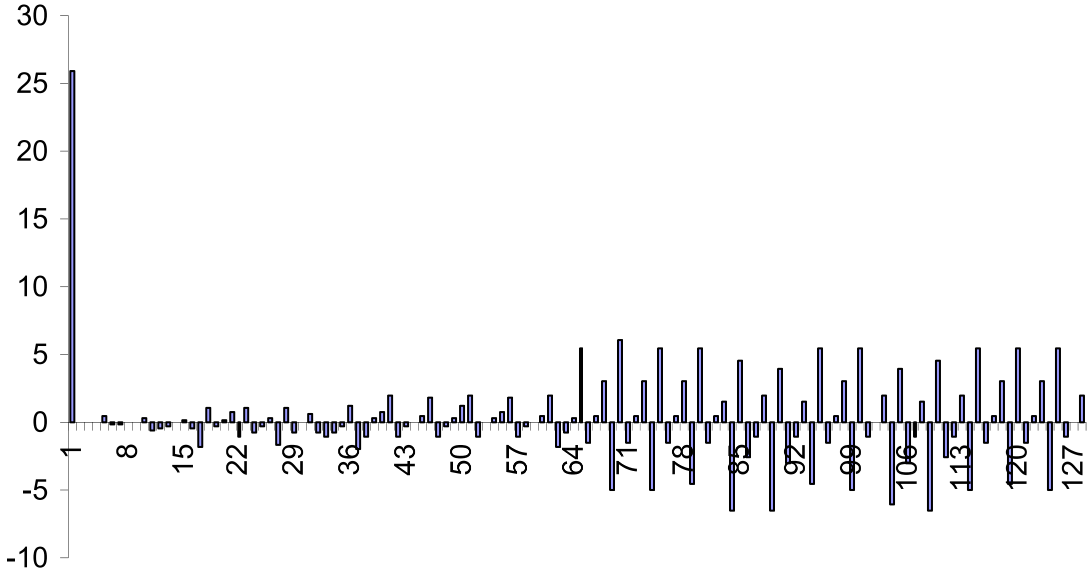

Fig.30. Current Haar spectrum for a faulty motor.

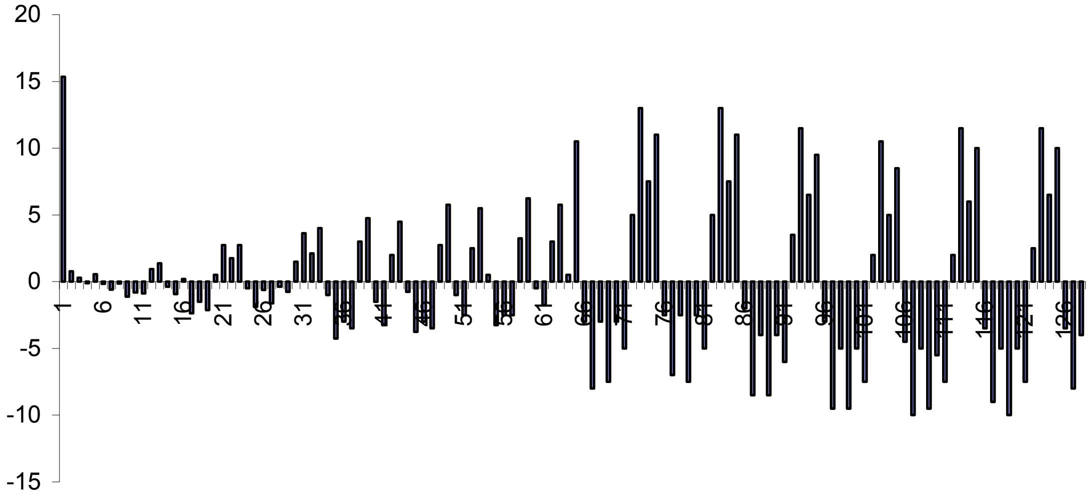

Fig.31. Current Haar spectrum for faulty control.

The carried out analysis included first 128 lines of the Haar spectrum for each individual signal. But it seems that such a big number of lines, corresponding to a considerable computational overhead, is not necessary for diagnostic purposes. It definitely increases the severity of numerical problems encountered in computations and requires high speed computationally effective microprocessors. Moreover, the experiments show that some components do not carry any useful information. Therefore it is essential for the intended expert system to have the ability of filtering spectra lines, i.e. to extract the substantial spectrum. In practice this resolves to making classification of individual components and reducing the number of spectra lines to an appropriate level, in accordance to the observations made by an experienced operator. A good solution here is to use data bases, storing the whole system history, as well as knowing and analyzing trends of signals related to individual state variables.

As an example in Fig.32 there are collectively presented 16 Haar spectra lines (this number was chosen to maintain readability of the figure) for different fault extents in thyristor T1. The data series mentioned there in the caption refer to the consecutive degrees of the fault. Considering Fig. 29 a distinctive spectra lines variability may be observed depending on the fault severity, as well as shifting leftwards their maximum value simultaneously with growing fault severity. Similarly the length of the first spectra line changes.

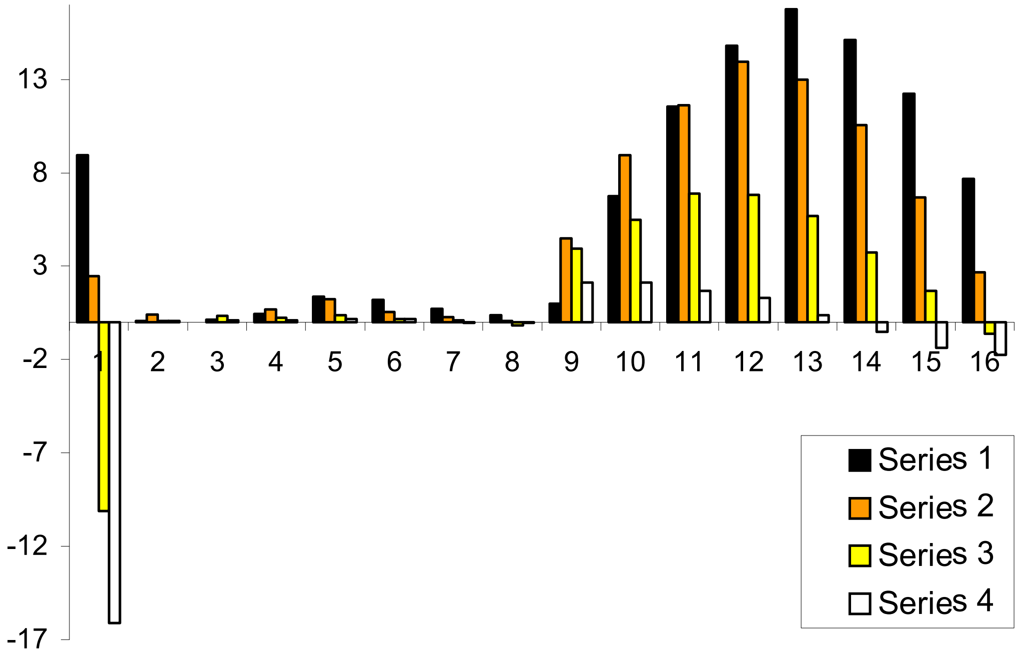

Fig.32. Haar spectra lines put together for different fault severities of the thyristor.

9. CONCLUSIONS

The point of this paper resolves in spectral analysis methods applied in fault detection and isolation. It is also assumed that the investigated time sets are realizations of stationary discrete processes fulfilling the hypothesis of ergodicism. Fast algorithms were used to accomplish the transforms. Particular attention was put to the model based diagnostic systems that execute fault detection and isolation, since they are more and more frequently applied and modified structures. It has been shown in the paper that the inverter currents and voltages in the frequency domain, as well as the ripples appearing in the DC link voltage and current depend on the working point and operating condition of the inverter. It is clearly seen from the carried out analysis that the appearing faults are accompanied by new components emerging in the investigated spectra, specific for the fault. New harmonics are modulated by the rectifier from AC to DC side and vice versa. These components are located within the bands adjacent to the lines corresponding to the normal operation of the inverter.

Analysis of the experiments described leads to the following conclusions:

- The nature of Haar spectra differs from each other for different kinds of the faults, which permits to isolate them, i.e. to state whether the fault occurs within the power supply, the load, control system or in the inverter itself.
- The nature of the spectra also depends on the kind of the investigated plant (the kind of the inverter and load).
- It seems reasonable to restrain the analysis to the initial 32 spectrum lines as this should provide accuracy enough for a fault identification.
- The increasing severity of a fault in the thyristor causes distinctive changes in the Haar spectrum layout. A remarkable change is observed in the value of the first spectrum line. At the same time the entire spectrum flattens, while the band of essential spectra lines becomes wider.
- It is suggested additionally to employ Haar spectrum of the voltage signal to make the diagnostics more smooth.
- It may be expected that monitoring selected signals in real time and getting their spectra in many cases would let to formulate diagnoses on the localization and extent of the probable faults. Unfortunately in some cases voltage or current spectra are not effective fault indicators. It is suggested in such cases to solve the problem by employing trend analysis techniques.

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DETEKCJA USZKODZEŃ W UKŁADACH ENERGOELEKTRONICZNYCH OPARTA NA MODELACH JAKOŚCIOWYCH I ILOŚCIOWYCH

W.JUSZCZYK, Z.R.KICH, M. ZAJĄC

STRESZCZENIE *Przyjęto, że monitorowanie stanu wybranego przekształtnika i jego układu sterowania jest powtarzalnym cyklicznie w sposób automatyczny komputerowym formułowaniem diagnoz o jego stanie. Innymi słowy jest to diagnozowanie prowadzone na bieżąco w czasie rzeczywistym. Autorzy założyli, że do celów diagnostyki układów energoelektronicznych wykorzystywane są głównie sygnały robocze, niewskazanym jest bowiem zakłócanie procesu dodatkowymi sygnałami testowymi.*

Przedstawiono typowe schematy możliwych testów diagnostycznych używanych do oceny własności wybranych sygnałów przekształtnika, oraz sklasyfikowano spotykane w literaturze metody detekcji uszkodzeń, które mogą znaleźć zastosowanie do oceny niezawodności działania podobnych układów energoelektronicznych.

Przedstawiono schemat blokowy procesu monitorowania przekształtnika. Szczególną uwagę zwrócono na przyczyny istnienia opóźnień czasowych powstawania symptomów. Sklasyfikowano czynniki od których zależą te opóźnienia. Zaproponowano formalizację opisu stanu pracy przekształtnika i opisu możliwych testów diagnostycznych. Do badań wybrano testy oparte na zastosowaniu analizy spektralnej sygnałów. Obiektem badań był typowy prostownik sterowany.

Zastosowanie teorii rozwinięć ortogonalnych umożliwiło przedstawienie stanu układu aproksymowanego ciągiem obserwacji jego wartości w postaci pewnej kombinacji liniowej funkcji bazowych. W badaniach zastosowano pełne rodziny binarnych funkcji ortogonalnych Walsha i Haara. Użyty w tej pracy algorytm szybkiego przekształcenia oparto na faktoryzacji macierzy Haara. Zastosowane metody badawcze można zaliczyć do metod numeryczno-analitycznych. Badania własności sygnałów prostownika przeprowadzono w oparciu o wykorzystanie szybkich algorytmów przetwarzania (w wersjach szeregowej i równoległej). Wykazały one swą przydatność dla formu-

łowania diagnoz o miejscach i zakresach pojawiania się typowych uszkodzeń w zasilaniu, sterowaniu czy też obciążeniu prostownika.

W połączeniu z modelowaniem symulacyjnym prezentowane podejście pozwoliło na przeprowadzenie kompleksowego procesu detekcji i lokalizacji uszkodzeń dla typowego układu prostownika sterowanego.

Wiesław Juszczyk D. Sc., was born in Kraków in 1947. He studied electrical engineering at the faculty of Electrical engineering in Mining and Metallurgy in the Mining and Metallurgy University (AGH) of Kraków, and was graduated there in the field of electrical engineering in metallurgy in 1970. In 1996 he obtained his Sc. D. degree.

He has been with the Department of Fundamental Research in Electrotechnics in the Institute of Electrical Engineering, branch in Kraków, since 1980.

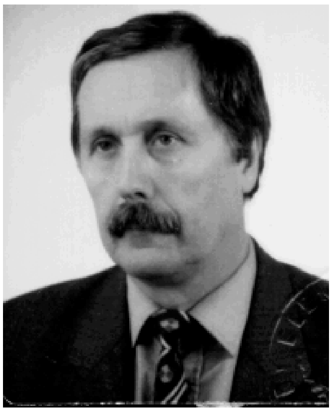
His scientific interests involve problems in the control of electric drives, parallel processing and drive systems diagnostics.

He is the author or contributed some 40 papers and conference lectures.

Zygmunt R. Kich M. Sc., was born in Kraków in 1941. He completed his studies in electrical engineering at the faculty of Electrical Engineering in Mining and Metallurgy in the Mining and Metallurgy University of Kraków (AGH), and received his M. Sc. Degree in the field of Telecommunication and Remote Control in 1972. The scope of his M. Sc. Work involved the use of acoustic signals in the diagnostic of an industrial plant. His first job was at Institute of Geohydrology at the same university, where he worked in mathematical modeling of underground water flow by means of electrohydrodynamic analogies, for which he was awarded a rector's prize. Later he moved to the Computer Centre of the Institute of Geophysics and Applied Geology in the same University. There he was involved in the centre's management and lecturing computer science to the students of Geological Faculty. His scientific interest comprised then geophysical data processing.

In 1980 he joined the Department of Fundamental Research in Electrotechnics of the Polish Academy of Sciences at the Institute of Electrical Engineering. He has been involved there in simulation and parallel computations in the control of electric drive systems.

He is the author or contributor of a number of papers and reports, of which several were presented in scientific conferences.



Mieczysław Zając D. Sc., was born in Kraków in 1949. During his university studies and thereafter he was involved in control theory and application of computer systems in modeling and optimization of industrial processes. The scope of his M. Sc. Comprised problems encountered in the construction of optimization algorithms using probabilistic methods.

After graduation he joined the Institute of Automatic Control and Industrial Electronics in the Mining and Metallurgy University of Kraków, while at the same time attending post-graduate studies for doctor's degree. In his disseration he investigated problems of the use of stochastic methods in the construction of a dynamic model of the hot-strip mill drives. In 1976 he passed a one year practise in Metallurgical Works in Kraków and then joined the Institute of Electric Drive Control.

In 1980 he joined the Department of Fundamental Research in Electrotechnics of the Polish Academy of Sciences at the Institute of Electrical Engineering. There he has been focused his scientific interest on the computer control of complex drive systems. In recent he has been involved in the use of parallel processing in the synthesis of drive systems' control.