Some Diagnosis Methods for Voltage Source Inverters
In Variable Speed Drives with Induction Machines
A Survey

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Abstract – Status monitoring and performance diagnosis for variable speed ac drives today is a need, more or less, depending on their application. Diagnosis can help to avoid unplanned standstill, to make possible to run an emergency operation in case of a fault or to keep the time to repair short in case of a fault. For the voltage source inverter several faults are possible. In this paper, these faults and their diagnosis are covered. Possible faults and remedial strategies are listed. It is enumerated, which faults in today’s standard protection systems are diagnosed. The main faults, in general not covered in these systems, are the transistor open circuit fault and the dc bus capacitor fault. In these fields diagnosis methods are under research. Some of the various reports of research groups in this field are outlined here as a survey with respect to function and properties.

I. INTRODUCTION

Automation of industrial processes has led to comprehensive electromechanical systems, where the electrical drive is important and in parts is the central component. Their production and operation costs are high. Therefore, the costs of planned standstill of these automation systems can be high, for unplanned standstill often much higher than for planned standstill. Breakdown or standstill of a single or dozens of drives often leads to the complete malfunction of the system.

Thus, for an economic operation a high utilization over time and short standstill times are required. This leads to the consequences, that in case of inevitable maintainance only short interruption times are allowed, unplanned standstill and faults have to be kept to a minimum and in case of possible faults short time to repair is necessary. Monitoring and diagnosis as well as preventive maintainance are valuable means to achieve this. All this depends on the economical conditions for the given system and its application.

The most common drive in industry is that with voltage source inverter and squirrel cage induction machine. Diagnosis of constant speed induction machines has been investigated for a long time and is well documented [1] and is commonly employed, generally by spectral analysis of mechanical and electrical signals. Applying these methods to converter fed machines seems possible, but there are only a few reports on results. Regarding diagnosis of converters, especially the voltage source pwm inverters, in comparison to electrical machines, there are a lot of components and faults to be diagnosed. Some of them are easy to diagnose and their diagnosis today is included in standard protection schemes. For others, diagnosis is difficult and not included in industrial converters. Investigations, resulting in lots of different methods presented in papers, have been carried out.

This paper gives a survey on function and properties of the diagnosis methods for voltage source inverters for induction machine drives with squirrel cage rotor. Typical faults are enumerated and the general diagnosis procedure is explained in section II. Section III comprises the diagnosis methods covered by the converter standard protection system. In section IV the transistor open circuit fault diagnosis is outlined, in section V the diagnosis of open circuit diode faults in the rectifier is presented. Section VI contents the diagnosis of growing faults and operation in fault mode. In chapter VII the dc bus capacitor diagnosis is outlined, chapter VIII contents the conclusion.

II. FAULTS AND DIAGNOSIS IN VOLTAGE SOURCE PWM POWER CONVERTERS

A. Faults

The basic drive with voltage source inverter and squirrel cage induction machine can be subdivided into the power converter, consisting of the machine side pwm inverter, the dc bus capacitor and the mains side diode rectifier, induction machine with squirrel-cage rotor and the control for the power converter and the drive.

Fig. 1: Variable speed ac drive with induction machine and voltage source inverter
The mains side can equally be equipped with a PWM rectifier, of which the diagnosis is quite similar to that of the PWM inverter.

The possible most important faults in voltage-fed inverters, either with mains side diode or transistor rectifier, for induction motor drives can be classified as following [2, 3]:
- ac line fault, single line to ground, line to line, missing line;
- dc bus fault, earth fault, capacitor short circuit fault, voltage limiting transistor fault;
- power semiconductor fault (transistor or diode in inverter or rectifier) short circuit or open circuit;
- dc link capacitor short-circuit fault;
- sensor faults, ac current sensor, dc bus voltage sensor etc.;
- faults in the control equipment.

The percentage of these faults for a switchmode power supply calculated on the base of a military reliability handbook are given here, they can give some idea about the possible distribution for the power converter: dc link capacitor 72 (60) %, power transistors 10 (31) %, inductive elements 4 (19) %, diodes 10 (3) % [8] (values in brackets for different circuit). Probably the high percentage for the capacitor is caused by the circuit design and the high frequency application, but in general this indicates, that the capacitor is to be taken into account concerning faults. Another previous report [9] on faults of variable speed ac drives in industry from 1995, with a rougher classification shows 38 % faults in converter power part, 53,1 % in control circuits and 7,7 % in external auxiliaries. The high control circuit fault rate may be caused by limited reliability of early days PWM control. An investigation of the effects of these faults on complete drive systems is given in [2].

Faults in the drive can be classified into three different groups:
- faults with total drive break down;
- faults with emergency operation possible,
- beginning fault with only small effects on the operation.

Besides diagnosis there is another way to improve the fault behaviour. To avoid faults or their consequences, according to the required reliability in the perspective application, for example higher reliability in space applications, the design concept has to be adapted, for higher reliability in general at higher costs:
- a „fault free“ design, for example with redundancies,
- a fault reduced design, for example with overdimensioning, for an increased mean time to repair,
- a fault tolerant design of the drive, for example with possible emergency operation,
- a design with increased protection measures, or
- a standard design related to faults and protection, for a required standard mean time to repair.

B. General Diagnosis Procedure

Diagnosis and monitoring in electrical variable speed ac drives usually is done by means of measuring, adapting and storing several measured signals from the drive as there could be voltage, current, flux, torque, vibration, speed or similar signals. Some of these signals are usually measured in a drive as they are necessary for control tasks. It would be very economical, if this number would be enough for diagnosis and monitoring. These signals are adapted to the application, i.e. filtered and often they are transformed as for example with Fourier Transform, Space Vector technique or Symmetrical Components. The next step is fault detection and the last step is fault localization and defining actions to be taken. For this, several techniques can be applied, most spread are knowledge-based ones as pattern recognition [3,4], but also average modelling, expert systems [5], Neural networks [6], Fuzzy logic or other kinds of Artificial Intelligence are used, often combined with fault classification or fault tree techniques [7].

Diagnosis here in general can be defined to run in three steps:
- data acquisition
- fault detection
- fault classification and determination of consequences.

For modern power converters and for power converters in electrical drives several reports concerning single aspects of status monitoring and fault diagnosis have been published. There are only few reports on total inverter or drive monitoring systems, as for example [Raison]. The field has been investigated more deeply since about 1990, thus results are relatively new.

III. DIAGNOSIS BY MEANS OF THE STANDARD PROTECTION SYSTEM

Today power converters in electrical drives designed for industrial use are equipped with more or less comprehensive protection systems. They enable protection against disturbances and execute a shut down in case of severe faults to avoid greater damage. The quantity of functions depends on the application. Basic protection functions which give diagnosis results are:
- fuses and fuse monitoring and drive shut down if a fuse is blown, via sensors and central control; for fuses in mains supply line and for control equipment as well as base drive power supply;
- power transistor overcurrent or short circuit detection with transistor switch off and drive shut down or controlled transistor restart, via desaturation detection circuits in the base drive and the main control;
- power transistor overvoltage detection and reduction, via circuits in the base drive;
- power converter overcurrent detection and reduction, via main control;
- mains supply voltage monitoring and shut down in case of undervoltage or missing line;
- power supply voltage monitoring and drive shut down in case of undervoltage.

This diagnosis functions of the standard protection system are partly carried out in the main microcontroller control system, partly in control subsystems. Nevertheless, a modern power converter is equipped with a lot of additional protection and thus also diagnosis functions as for example fan diagnosis or
maximum current limitation according to the ambient temperature, which will not be presented here in detail. They can count up to 50 or more functions.

Thus, a today’s industrial drive is well equipped with diagnosis functions, but there are still functions that in general are not covered because of several reasons as necessary additional sensors or necessary higher computing power or missing diagnosis methods. Regarding the fault distribution in a power converter given before as an example, there are two important diagnosis functions that have not been covered by the ones listed above as there are power transistor open circuit faults and dc bus capacitor faults.

IV. POWER TRANSISTOR OPEN CIRCUIT FAULT DIAGNOSIS

Power semiconductor faults in power converters are subdivided into short circuit and open circuit. Short circuit of these elements in most cases causes an overcurrent, detected by the standard protection system, and a shut down of the drive is carried out. Further operation is not possible, a repair is necessary. The standard protection system in power converters today can locate the defective element, thus giving information for the repair.

A. Behaviour with Transistor Open Circuit

Voltage Source PWM power converters with an open transistor fault show a typical current wave form in the time domain, see figure 2 for steady state fault condition. The current in one phase becomes zero during a part of the period and it is unsymmetrical. The converter continues to operate. Because of the irregular current waveform, the operation is affected. The fault has to be detected and as a consequence, stop of operation or emergency operation, has to be decided.

If the three phase current signal is transformed into the two phase $\alpha,\beta$-space vector representation, the current space vector trajectory is a circle in fault free operation, figure 3.a. In case of an open transistor fault the ac current space vector trajectory shows a typical fault pattern, too, it becomes a semicircle, figure 3.b. The relative position of the of the semicircle is characterising the defect transistor [3, 10].

\[
\Psi = \frac{i_{\alpha k} - i_{\alpha(k-1)}}{i_{\beta k} - i_{\beta(k-1)}}
\]

This gives for a faulty transistor a constant value during that time when the current vector takes the course on the diameter, the quantity, three values are possible ($-\sqrt{3}, \sqrt{3}, \infty$).

For power semiconductor with open circuit fault, therefore the diagnosis approach of ac current signature analysis (ASCA), either in time domain or in space vector representation, is an appropriate one.

B. AC Current Space Vector Trajectory Slope Analysis

Localization of the fault can be done with the ASCA method by calculation of the slope $\Psi$ of the diameter of the current space vector trajectory [3]. With $i_{\alpha k}, i_{\beta k}$... the sampled $\alpha,\beta$-components of the current the slope can be calculated from:

\[
\Psi = \frac{i_{\alpha k} - i_{\alpha(k-1)}}{i_{\beta k} - i_{\beta(k-1)}}
\]
defines the faulty leg. The defect transistor in the leg, upper or lower one, can be detected by determining which alternation of the current is missing in the faulty phase.

There is a simple calculation formula and a direct fault detection to be stated.

C. AC Current Space Vector Average Quantity Approach

The fault signature in figure 3, middle, shows a characteristic waveform with an uncentered midpoint of the current trajectory, which is typical for the fault case. This is equivalent to dc components in the ac currents in case of fault, which are obvious from figure 2.

Thus, the fault occurrence detection and defect transistor localization can be done by calculating and analysing the position of the current trajectory’s midpoint [11], which means the mean value of the ac current space vector (Park’s vector) over one period. This is done by first calculating the mean value of the phase currents \( \langle i(t) \rangle \) and then transforming the result into an average value space vector \( \bar{I}_{ac} \) according to eq. (1). Its amplitude and phase angle characterise the fault. The measured average space vector current data in table 2, left, well confirm the considerations on figure 3. Out of that the knowledge base for fault detection and localization can be set up, table 2, right.

<table>
<thead>
<tr>
<th>Experimental Results</th>
<th>Derived Knowledge base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistor</td>
<td>( \bar{I}<em>{ac} / I</em>{acN} )</td>
</tr>
<tr>
<td>T1 1.59</td>
<td>181.04</td>
</tr>
<tr>
<td>T2 1.68</td>
<td>240.01</td>
</tr>
<tr>
<td>T3 1.75</td>
<td>298.25</td>
</tr>
<tr>
<td>T4 1.75</td>
<td>0.41</td>
</tr>
<tr>
<td>T5 1.52</td>
<td>58.96</td>
</tr>
<tr>
<td>T6 1.46</td>
<td>114.54</td>
</tr>
</tbody>
</table>

The current limit for fault detection has to be well defined between zero and the minimum steady state fault current (0< \( I_{lim} / I_{acN} \) (eq. (1))) to enable early detection as well as robust operation. For this method, the calculation is simple. Nevertheless, the use of a mean value could effect the time response negatively.

D. AC Current Space Vector Instantaneous Frequency method

Another diagnosis method for open circuit transistors is the instantaneous frequency method [3]. As the frequency of the current space vector is zero when it is moving on the diameter of the semicircle at open circuit fault, see figure 3, the detection of faults can be done by this feature. The instantaneous frequency \( f_i \) of the ac current space vector can easily be calculated from the sampled current data by:

\[
f_i = \frac{1}{2 \pi} \arg \left( \frac{i(k) \cdot i(k-1) - i(k-1) \cdot i(k)}{i(k-1) \cdot i(k-1) - i(k) \cdot i(k)} \right)
\]

For a test system, with this method a failure detection time of 20 ms was achieved.

The formula is somewhat less simple compared to the ones presented before. A direct detection is possible.

E. AC Current Space Vector versus Rotation Angle Fundamental Method

Diagnose of an transistor open circuit fault and its location can also be done by analysing the difference of the amplitude of actual and reference ac current space vector versus rotation angle[10]. The diagram in figure 5 shows this curve for steady state fault. The irregularities in case of a fault are detected by performing a Discrete Fourier Transform (DFT). The amplitude of the fundamental, which in case of a fault becomes greater than zero, indicates the fault case. The phase angle of the fundamental indicates the position of the defect transistor.

*Fig. 5: Deviation of ac current space vector versus rotation angle for open transistor fault[10] (\( \zeta_k \) amplitude of current space vector deviation value; \( k \) proportional to the angle of current vector rotation, \( k = 32 \) equal to 360 degree)*

This method with DFT is more complex. The fault detection is not done in a direct way, but via the DFT for which a signal of minimum length (1 period) is necessary.

F. Comparison of AC Voltage Actual and Reference Quantity Approach in 'Time Domain

Most methods take about one fundamental period to detect the fault occurrence. There have been also special methods developed to minimize the time between fault occurrence and detection [12]. One possibility is to analyse the ac side or motor side voltages, terminal to star point (\( V_{kn} \), phase k, neutral n) or terminal to midpoint (\( V_{kn0} \), midpoint of the dc link capacitors). They show irregularities at open circuit faults (\( V_{kn0} \) voltage machine neutral to midpoint of the dc link).
These voltages can be monitored and these irregularities can be detected, which gives a direct location of the faulty transistor position as has been derived. A fault detection table can be derived, see table 2 ($\Delta v_{1n}$ measured voltage ac terminal to star point of load; $\Delta v_{0}$ voltage ac terminal to midpoint dc link as result of open transistor).

**TABLE 2**

<table>
<thead>
<tr>
<th>$\Delta v_{1n}$</th>
<th>$\Delta v_{2n}$</th>
<th>$\Delta v_{3n}$</th>
<th>Defect Transistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/3 $\Delta v_{10}$</td>
<td>-1/3 $\Delta v_{10}$</td>
<td>-1/3 $\Delta v_{10}$</td>
<td>T1</td>
</tr>
<tr>
<td>-1/3 $\Delta v_{20}$</td>
<td>2/3 $\Delta v_{20}$</td>
<td>-1/3 $\Delta v_{20}$</td>
<td>T2</td>
</tr>
<tr>
<td>-1/3 $\Delta v_{20}$</td>
<td>-1/3 $\Delta v_{20}$</td>
<td>2/3 $\Delta v_{20}$</td>
<td>T3</td>
</tr>
<tr>
<td>-2/3 $\Delta v_{10}$</td>
<td>1/3 $\Delta v_{10}$</td>
<td>1/3 $\Delta v_{10}$</td>
<td>T4</td>
</tr>
<tr>
<td>1/3 $\Delta v_{20}$</td>
<td>-2/3 $\Delta v_{20}$</td>
<td>1/3 $\Delta v_{20}$</td>
<td>T5</td>
</tr>
<tr>
<td>1/3 $\Delta v_{20}$</td>
<td>1/3 $\Delta v_{20}$</td>
<td>-2/3 $\Delta v_{20}$</td>
<td>T6</td>
</tr>
</tbody>
</table>

This is also a kind of knowledge based procedure. Detection times of one fourth of a period have been attained. There are several similar ways possible, based on other voltages. This method can also be transferred to a current based approach [12]. As there is no current reference signal, in that case this can be obtained from a parallel running machine model. However, the analysed signal has conceptually well to be chosen to avoid incorrect detection in case of machine unsymmetry.

The detection is quite simple and direct. For this fast detection in some cases extra sensors are necessary, for example for the load star voltage.

**G. Current Pattern Recognition Method in Time Domain**

The fault modes of the complete converter system in figure 1 can be characterized by patterns derived from the three phase current waveform in time domain [4]. The pattern characteristic is defined by three parameters: the dc offset value, the polarity of the average current value in the first quarter of a complete period and in the second quarter. Each one can be equal to zero, greater than or lower than zero. In case of a semiconductor fault, nine of the total 27 parameters, called flags, are set in a special way and enable the detection of a fault. The distribution of the flags characterises the defect semiconductor.

**TABLE 3**

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta v_{1n}$</td>
<td>$\Delta v_{2n}$</td>
<td>$\Delta v_{3n}$</td>
</tr>
<tr>
<td>&gt;0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&lt;0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>=0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Here, many signals have to be processed. Additional equipment as for example current zero crossing detection is necessary. On the other hand, direct detection is performed.

**H. Converter Behaviour Rules Diagnosis in Time Domain**

For a VSI commutation cell, a phase leg of the converter, considered as a black box, the switching state can be determined by means of obvious behaviour rules. For example see figures 1 and 2: positive ac voltage means upper branch open, positive current means transistor, negative means diode is conducting. This determination is based on the measured dc bus current in each leg, the ac currents and ac voltages. This concept can be transferred to a three phase converter.

As the dc current for each leg, base for applying this method, is difficult to measure, its virtual quantity can be calculated by checking Kirchhoff’s laws for the currents for all possible switching states. This knowledge base of behaviour rules has been implemented into an expert system and been proven to run in an off-line mode [13].
sition into an online expert system should prove the function. The detection is direct.

I. Spectrum Analysis Method

Some remarks concerning spectrum analysis methods, for converters, widely used for diagnosis in electrical machines [1], are given in [14]. For an open transistor a characteristic current spectrum is given and can be analysed for detecting a fault. Therefore Fast Fourier Transformation with high computing power is necessary and thus the detection is not a direct one.

VI. DIODE RECTIFIER OPEN CIRCUIT FAULTS DIAGNOSIS

A. Spectrum Analysis Method

Some remarks concerning AC Current Analysis: Mains side diode rectifier faults, short or open circuit, result in typical irregular space vector current trajectories in a way equivalent to the transistor inverter. These can be analysed for the fault diagnosis [15, 16], in some way equivalent to the methods for transistor inverters or rectifiers. The properties are similar to that shown in the previous chapter. Therefore, this field will not be deepened.

B. Symmetrical Space Phasor Components Approach

In fault free operation of a cyclic operating diode bridge converter circuit, voltages and currents are symmetrical. In case of faults they become asymmetrical. By means of representation of the electrical quantities in symmetrical space phasor components, a combination of space phasors and symmetrical components, the symmetrical and asymmetrical components can be separated [17]. Representation of electrical quantities in symmetrical space phasor components leads via the space vector, see equation (3), to homopolar or zero component \( Y^{(0)}(t) \), positive sequence component \( Y^{(1)}(t) \) and negative sequence component \( Y^{(2)}(t) \):

\[
\begin{bmatrix}
Y^{(0)}(t) \\
Y^{(1)}(t) \\
Y^{(2)}(t)
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 \\
1/a^2 & a & a^2 \\
1 & a & a^2
\end{bmatrix} \begin{bmatrix}
Y(t) \\
Y(t + T/3) \\
Y(t + 2T/3)
\end{bmatrix}
\]

(4)

For a six pulse bridge configuration, a diode bridge is being investigated, it is shown to be useful to extend this representation to six components. The trajectory of each symmetrical component space phasor has to be calculated and analysed.

The trajectories show special patterns, nevertheless, detection of faults will be difficult and a high processing power is necessary. The detection is not done directly, as patterns for some periods are necessary for detection.

Fig. 8: Symmetrical Space Phasor Components Approach, current trajectories of a bridge with diode fault [17]

VI. DIAGNOSIS OF GROWING FAULTS AND OPERATION IN FAULT MODE

To increase the reliability of power converters, not only post fault diagnosis is sufficient, but also diagnosis of growing faults, especially in power semiconductors, is necessary. Growing faults arise for example from losing of the bond wires. This results in higher collector emitter saturation voltage. However, results presented in [18] show, that it is a difficult task to measure and detect this irregularities and it is open if it will lead to reliable results. Therefore this field will not be presented here more deeply.

In case of faults often it is necessary to keep the drive operating, maybe with decreased load capacity. Some research work on this field has been reported to enable and optimize motor operation when fed from an inverter with one phase missing because of a fault, i.e. with a two phase feeding. The starting has been analysed and optimised [19] as well as a method to run the drive with a smoothed torque despite of two phase feeding [20].

VII. DIAGNOSIS METHODS FOR DC BUS CAPACITORS

DC bus electrolytic capacitors have a limited lifetime, which is often shorter than that of the power semiconductors. So, there is a big need to include them into the diagnosis. DC bus capacitor failures can be subdivided into total break downs and growing faults. In the case of a total break down, which corresponds to a blown fuse of the capacitor, the converter will usually be shut down because of an insufficient smoothing effect in the dc link. In case of a growing fault beyond a limit to be defined, a preventive maintenance is necessary to avoid further growing and following total break down.
The aging in the capacitor can be characterised on the base of its increasing internal series resistance $ESR(t)$, 

$$\frac{1}{ESR(t)} = \frac{1}{ESR(0)} \cdot (1 - k \cdot t \cdot \exp(-\frac{4700K}{T - 273K}))$$  \hspace{1cm} (5)

($T$: aging temperature, $t$: aging time, $ESR(0)$: resistance $ESR$ at time $t = 0$; $k$: constant depending on design and construction of the capacitor)

which can be taken for diagnosis of the remaining lifetime [21]. The internal resistance increases remarkably during lifetime of the capacitor. For high frequency operation as with VSI pulse width modulation, the capacitors impedance

$$Z = ESR + j\omega \cdot ESL + \frac{1}{j\omega C} = ESR$$  \hspace{1cm} (6)

is mainly constituted by the internal resistance component. The stray inductance and capacitor component can be neglected.

$$u_{C,ac} = ESR \cdot i_C$$  \hspace{1cm} (7)

Thus, the capacitor current, an ac current, causes an ac voltage mainly at the resistive component of the capacitor.

**Fig. 9: Current and rectified fundamental voltage in a switch mode power supply at transient for new and aged capacitors [21]**

By means of measurement over time of both the current and the ac component of the dc voltage at the capacitor, the resistance $ESR(t)$ and so its increase and capacitor aging can be determined.

The influence of the ambient temperature and the case heating with the additional influence of current and voltage has to be regarded, too. To get the exact determination and avoid the disturbing influence of transient conditions, the fundamental of the ac voltage and current should be taken for calculation.

**Fig. 10: DC bus capacitor lifetime prediction via internal resistance [22]; Calculation scheme for internal resistance by means of voltage fundamental with influence of ambient temperature, voltage and current**

In a prediction model the future growing of the internal resistance $ESR$ and the remaining lifetime, represented by a limit value for $ESR$, can be evaluated. Data acquisition and diagnosing must be accurate, but must because of the slow aging process no fast computing is necessary.

VIII. CONCLUSION

A survey on some diagnosis methods for voltage source converters in electrical drives with induction machines is presented with respect to function and properties. The diagnosis methods of the total converter are outlined shortly. The focus is put on the diagnosis of these converter components, where there is still a high activity of investigation, thus the status of technique still is not fixed. These are the open circuit semiconductor faults and the dc bus capacitor faults. In this field, many different methods have been presented with promising properties suitable for future applications.

IX. REFERENCES


