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# Rotating electrical machines

## Part 24: Online detection and diagnosis of potential failures at the active parts of rotating electrical machines and of bearing currents — Application guide

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## National foreword

This Draft for Development is the UK implementation of CLC/TS 60034-24:2011. It is identical to IEC/TS 60034-24:2009.

The UK participation in its preparation was entrusted to Technical Committee PEL/2, Rotating electrical machinery.

A list of organizations represented on this committee can be obtained on request to its secretary.

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# Rotating electrical machines - Part 24: Online detection and diagnosis of potential failures at the active parts of rotating electrical machines and of bearing currents - Application guide
(IEC/TS 60034-24:2009)

Machines électriques tournantes -
Partie 24: Détection et diagnostic en ligne de défaillances potentielles des parties actives de machines électriques tournantes et de courants de palier -
Guide d'application
(CEI/TS 60034-24:2009)

Drehende elektrische Maschinen -
Teil 24: Erkennung und Diagnose von möglichen Schäden an den Aktivteilen drehender elektrischer Maschinen und von Lagerströmen -
Anwendungsleitfaden
(IEC/TS 60034-24:2009)

This Technical Specification was approved by CENELEC on 2011-01-25.

CENELEC members are required to announce the existence of this TS in the same way as for an EN and to make the TS available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force.

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CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

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# Foreword

The text of the Technical Specification IEC/TS 60034-24:2009, prepared by IEC TC 2, Rotating machinery, was submitted to the formal vote and was approved by CENELEC as CLC/TS 60034-24 on 2011-01-25.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following date was fixed:

| | | |
|---|---|---|
| – latest date by which the existence of the CLC/TS has to be announced at national level | (doa) | 2011-07-25 |

# Endorsement notice

The text of the Technical Specification IEC/TS 60034-24:2009 was approved by CENELEC as a Technical Specification without any modification.

# INTRODUCTION

Progress in design and technology has resulted in an increasing reliability of rotating electrical machines, but failures could not be eliminated completely. Since the demand for a high availability is permanently increasing, it is essential to detect deficiencies at an early stage and to recognize the origin and identify the severity of the fault in order to estimate the risk of a continuation of operation.

It would be advantageous, if the signals which are obtained by the detection methods presented in this guide, were suitable to distinguish the different failures from each other. By this means, the signal analysis can be used as input data of a complete monitoring system.

The aim of this guide is to present possible tools which are available for the intended purpose and to explain their advantages and disadvantages. The minimum requirements which shall be met by the various sensors will be discussed, whereas the detailed design rules are outside the scope of this technical specification.

This guide deals with the detection of failures at the active parts of multi-phase rotating machines (all kinds of winding faults in stator and rotor, cage deficiencies, eccentricities) and of bearing currents. DD CLC/TS 60034-24:2011

# ROTATING ELECTRICAL MACHINES –

# Part 24: Online detection and diagnosis of potential failures at the active parts of rotating electrical machines and of bearing currents – Application guide

## 1 Scope

This part of IEC 60034 is applicable to the on-line detection and diagnosis of failures at the active parts of multi-phase rotating electrical machines (induction and synchronous machines) and of bearing currents. The failure analysis includes:

- interturn faults;
- phase-to-phase short-circuits;
- double earth faults and single earth faults of motors with earth connection of the star-point;
- static and dynamic eccentricities;
- cage imperfection or defects (e.g. broken bars or end-rings);
- bearing currents.

This can be achieved by tools like search coils or other magnetic sensors or partly by the analysis of the terminal voltages and currents.

The detection of the following effects is excluded from the scope:

- vibration (covered by ISO standards, e.g. ISO 10816 and ISO 7919);
- partial discharge (covered by IEC 60034-27);
- single earth-faults of motors without earth connection of the star-point;
- core imperfection.

Also excluded are special methods applicable for specific applications only (e.g. turbo generators).

## 2 Normative references

There are no normative references in this technical specification.

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

**3.1**
**distribution factor**
the factor, related to a distributed winding, which takes into account the reduction in the generated voltage due to the phase difference between the voltages generated in the coils in different slots

[IEV 411-38-37]

### 3.2

**chording (pitch) factor**

the factor, related to a distributed winding, which takes into account the reduction in the generated voltage, when the winding pitch is not 100 %

[IEV 411-38-38]

### 3.3

**branch factor**

the factor, related to a distributed winding, which takes into account the reduction in the generated voltage due to the phase difference between the voltages generated in the series-connected branches

## 4 Basis of the diagnosis

The ability of electrical machines to operate is based on the existence of a magnetic field in the air-gap, which is looping in a cross-sectional area of the laminations of stator and rotor. Flux components in the end-portions of the machine outside the cores are of a parasitic nature. Therefore available signals suitable for the detection of potential faults originate from the magnetic field in the air-gap, which shall be analyzed in order to distinguish between those components which occur under regular operating conditions and those components which are attributed to a specific failure and which do not exist in a healthy machine.

Since the winding producing the magnetic field consists of coils distributed symmetrically around the circumference and since the sum of the supplying currents is usually zero, the air-gap field forms also a periodic function along the circumference. The wave of the flux density can be considered as the superposition of a sum of sinusoidally distributed waves, which are characterized by the following features:

- amplitude,
- number of pole-pairs,
- angular velocity,
- phase-angle,
- type of wave (rotating or standing).

Table 1 shows the composition of the air-gap field in the case of a three-phase cage induction motor, which is equipped with an integral slot winding. The table can easily be extended to be valid also for fractional slot windings. Similar tables can be developed for slip-ring motors and all kinds of synchronous machines.

**Table 1 – Most important magnetic fields in the air-gap of a three-phase cage induction motor with an integral slot stator winding under normal operating and fault conditions**

| Origin of the field | | Stator fields | Rotor fields | Item |
|---|---|---|---|---|
| **Fields under normal operating conditions** | winding fields<br>(slot harmonics) | type: rotating<br>frequency: $f_1$<br>number of pole pairs: $\nu_1 = p\ (1 + 6g_1)$<br>$g_1 = 0; \pm 1; \pm 2; \dots$<br>(slot harmonics: $\nu_1 = p + g_1\ Q_s$) | type: rotating<br>frequency: $f_1\left\{1+\frac{g_2 Q_r}{p}(1-s)\right\}$<br>$g_2 = 0; \pm 1; \pm 2; \dots$<br>number of pole pairs: $\nu_2 = \nu_1 + g_2\ Q_r$ | 1 |
| | saturation fields | type: rotating<br>frequency: $3f_1$<br>number of pole pairs: $\nu_1 = 3p$ | type: rotating<br>frequency: $f_1\left\{3+\frac{g_2 Q_r}{p}(1-s)\right\}$<br>$g_2 = 0; \pm 1; \pm 2; \dots$<br>number of pole pairs: $\nu_2 = 3p + g_2\ Q_r$ | 2 |
| **Additional fields under fault conditions** | interturn faults<br>phase-to-phase faults<br>double earth faults | type: superposition of reverse rotating fields of different amplitude<br>frequency: $f_1$<br>number of pole pairs: $\nu_1 = 1; 2; 3; \dots$ | type: superposition of reverse rotating fields of different amplitude<br>frequency: $f_1\left\{\pm 1+\frac{g_2 Q_r}{p}(1-s)\right\}$<br>$g_2 = \pm 1; \pm 2; \dots$<br>+ positive-sequence fields<br>– negative-sequence fields<br>number of pole pairs: $\nu_2 = \nu_1 + g_2\ Q_r$ | 3 |

| Origin of the field | Stator fields | Rotor fields | Item |
|---|---|---|---|
| eccentricity | type: 2 rotating fields<br>frequency: $f_1\{1 \pm \frac{K}{p}(1-s)\}$<br>$K$ = 0: static eccentricity<br>$K$ = 1: dynamic eccentricity<br>number of pole pairs: $\nu_1 = p \pm 1$ | type: 2 rotating fields<br>frequency: $f_1\left\{1+\left[\pm\frac{K}{p}+\frac{g_2 Q_\mathrm{r}}{p}\right](1-s)\right\}$<br>number of pole pairs: $\nu_2 = \nu_1 + g_2 \; Q_\mathrm{r}$<br>$g_2 = 0; \pm 1; \pm 2; \ldots$ | 4 |
| rotor asymmetry | | type: superposition of reverse rotating fields of the same amplitude<br>frequency: $f_1\left\{\pm s+\frac{\nu_2}{p}(1-s)\right\}$<br>number of pole pairs: $\nu_2 = 1; 2; 3; \ldots$ | 5 |

**Symbols**:

$f_1$ fundamental frequency

$p$ number of pole pairs, for which the motor is designed

$\nu$ number of pole pairs in general

$Q_\mathrm{s}$ number of stator slots

$Q_\mathrm{r}$ number of rotor bars

$s$ slip

## 5 Kinds of electrical signal analysis

### 5.1 General

A valuable detection method shall be able to detect failures at an early stage. Therefore signals disclosing a rapid change in the case of small deficiencies, are optimal for the intended purpose. By contrast signals which vary only insignificantly should not be used as the basis of the diagnosis.

The signal processing needs the availability of appropriate electronic equipment. Although the resolution of modern devices is high, signals which do not need excessive precision should be preferred in this respect.

### 5.2 Stator current/voltage analysis

The analysis of the terminal voltages or currents of a rotating machine allows identification of

- different frequencies,
- positive-, negative-, and zero-sequence components,
- different amplitudes of the components.

In general, all waves of induction in the air-gap field can induce voltages of certain frequencies in the stator winding and can cause currents of the same frequencies. The additional current components which are generated by a specific failure are superimposed to the supply values during undisturbed operation. All details shall be taken from the relevant table, that is Table 1 in the case of three-phase cage induction motors.

Table 1 is worded for one single supply frequency $f_1$. However, in case of a converter supplied machine, it is valid for each voltage/frequency component, which is contained in the output spectrum of the converter.

Table 1 shows the components of the air-gap field. Whether a specific component induces a voltage in the stator winding, depends on its winding factor for the number of pole pairs under consideration. The winding factor is the product of the following terms:

- the distribution factor,
- the chording factor,
- the branch factor.

The branch factor is not generally known amongst engineers, but of fundamental importance for the problem under consideration. Each symmetrical three-phase integral slot winding consists of $p$ (in case of a single-layer winding) or $2p$ (in case of a double-layer winding) identical coil groups (branches), which are distributed symmetrically around the circumference. They can be series-connected or connected to form parallel branches with the maximum number $a = 2p$. The connecting method considerably influences the branch factor of a specific number of pole pairs.

It can be shown that the branch factor is zero for the eccentricity fields $\nu = p + 1$ and $\nu = p - 1$ for all windings with series-connection of the coil-groups. *Consequently both types of eccentricity cannot be detected for such machines by stator current analysis.*

The branch factor of the harmonic fields according to item 1 to 4 of Table 1 depends also on the individual configuration and in addition on the number of rotor slots. The design of a given case is selected by the manufacturer of the machine for different reasons (e.g. to suppress unbalanced magnetic pull, to avoid nasty magnetic tones, etc.) and unknown to the user. *It is therefore not advisable to use the harmonic rotor fields of items 3 and 4 as the signal for a stator current analysis.*

The group of winding faults in item 3 marks the most severe deficiencies at the active parts. They all produce magnetic fields of fundamental frequency. *Thus winding faults cannot be detected by a frequency analysis of the stator currents.*

The field waves, produced by winding faults, are of elliptic nature, which means the superposition of two reverse rotating waves, having the same number of poles and the same frequency, but different amplitudes. In principle such failures can be detected by exploring the negative sequence component of the current of fundamental frequency.

Especially in case of the most dangerous failure, an interturn fault of a high-voltage machine, when the high currents flow in only one of many turns per phase, this component is very small. A negative-sequence component of the current may also be caused by an unavoidable small asymmetry of the supply voltages (a negative sequence component of the voltage results in a negative sequence component of the currents, which is 6 to 10-times higher). *Summing up, it is not recommendable to detect winding faults by means of a voltage/current analysis.*

Reliable detection of cage imperfection or defects (e.g. broken bars or end-rings) is possible by use of stator current analysis.

Another disadvantage of the stator current analysis cannot be neglected. Statistics of insurance companies manifest that most of the winding faults occur during transient phenomena such as starting of motors, short-circuits at the terminals, etc., and cause high inrush currents. It is unfeasible to detect failures by current analysis during the interval of the transients.

### 5.3 Induced voltages of auxiliary turns embedded into the stator slots or other magnetic sensors sensing the air-gap flux

An ideal diagnostic signal would be zero during operation of a healthy machine under steady-state and transient conditions, it would rise with the amount of the deficiency for all kinds of failures according to items 3 to 5 of Table 1 and would be able to distinguish between the failures. Solutions close to the optimum have been developed.

These solutions are based on turns made by insulated wire, the diameter of which can be selected under solely mechanical aspects. Both coil-sides are incorporated in the stator slots of the main winding, usually during manufacturing of the machine between the upper layer of the winding and the slot wedge. The assembly at a later stage is possible. The end-connections are led close to the end of the core.

The same insight into the magnetic field at specific locations at the stator bore can eventually be achieved by other kinds of magnetic sensors instead of measuring turns.

Usually several turns of the same pitch are series-connected and shifted against each other by a predetermined angle. It is aimed to get finally a system of auxiliary measuring coils, for which the resulting winding factor is zero for all air-gap fields, which exist during normal undisturbed operation, and for which the winding factor is maximum for a field with that number of pole pairs, which is intended to be used as the reference field of the diagnosis.

If a system of auxiliary coils can be found which fulfills the condition explained above for a reference field, which is amongst the fields generated by all failures of items 3 to 5, the coil system would be complete. But there is one remaining difficulty: The fields produced by a winding fault according to item 3 of Table 1, are of an elliptic nature. If one of them is chosen as reference field, the induced voltage of the coil system would vary with the location of the fault at the circumference. Such a situation is of course unacceptable.

The problem can be eliminated by use of a second identical coil system, which is shifted against the first one by the angle $\pi/(2\nu)$, when $\nu$ is the number of pole pairs of the reference field. Then both coil groups form a symmetrical two-phase system, which easily allows the calculation of the symmetrical components (SC) of the two measured voltages. The SCs are independent of the fault location.

This guide is the inappropriate place to explain the design rules for the coil system in detail. It is mentioned only that the minimum number of turns per coil system usually varies between 6 and 12 depending on the data of the relevant machine and the claims to the sensibility of the diagnosis.

The reference field is taken from the list of air-gap fields, which are generated by the fault condition and which are zero during normal operation. Therefore the amplitude of the reference field is nearly unchanged during transients. This statement is proven by tests.

The procedure of the diagnosis is executed in Table 2. Winding faults are characterized by the criterion that both (positive and negative sequence) symmetrical components do exist and have mains frequency. The voltages in case of static eccentricity have mains frequency too, but the negative-sequence component $U_\mathrm{n}$ is zero. A dynamic eccentricity can be distinguished from other fault conditions by the typical frequencies of the induced voltages. Rotor asymmetries are marked by other typical frequencies; the induced voltages become zero, when the machine is running at synchronous speed ($s$ = 0), because then the rotor currents, responsible for the reference field, disappear.

*It can be concluded that a professionally designed system of auxiliary coils forms a useful tool for the detection and diagnosis of faults.*

For the purpose of completeness it should be mentioned that other types of search coils were proposed in technical articles, which e.g. comprise one stator tooth only. They may be useful to investigate a specific effect, but they are unsuitable to form a complete diagnosis and were therefore not introduced into engineering practice.

**Table 2 – Diagnosis of failures at a cage induction motor, equipped with two identical auxiliary coil systems**

| **Kind of faults** | **Measured quantities** | | | | |
|---|---|---|---|---|---|
| | $f$ | $U_1$ | $U_2$ | $U_p$ | $U_n$ |
| Winding fault | $\boxed{f = f_1}$ | $U_1 \neq 0$ | $U_2 \neq U_1 \neq 0$ | $U_p \neq 0$ | $\boxed{U_n \neq 0}$ |
| Static eccentricity | $\boxed{f = f_1}$ | $U_1 \neq 0$ | $U_2 = U_1$ | $U_p \neq 0$ | $\boxed{U_n \neq 0}$ |
| Dynamic eccentricity | $\boxed{f = f_1 \left\{ 1 \pm \frac{1}{p}(1-s) \right\}}$ | $U_1 \neq 0$ | $U_2 = U_1$ | | |
| Rotor asymmetry | $\boxed{f = f_1 \left\{ \frac{1}{p}(1-s) \pm s \right\}}$ | $U_1 \neq 0$ | $U_2 = U_1$ | | |

**The marks of identification are indicated by a bold frame.**

| **Symbols:** | | |
|---|---|---|
| | $U_1$, $U_2$ | r.m.s. values of the measured voltages of the coil systems 1 and 2 |
| | $\underline{U}_p = \frac{1}{2}\left(\underline{U}_1 + j\underline{U}_2\right)$ | positive-sequence component of the measured voltage |
| | $\underline{U}_n = \frac{1}{2}\left(\underline{U}_1 - j\underline{U}_2\right)$ | negative-sequence component of the measured voltage |

### 5.4 Induced voltages of search coils collecting axial fluxes

Proposals were made to use either toroidal coils, fastened in front of the machine or coils surrounding the shaft of the machine. In both cases the axial flux produced by the machine is intended to be used for the detection of failures. Such approaches are generally not beneficial for the following reasons.

Axial flux components are always parasitic and undesired, because the performance of the machine is based on flux components looping in the cross-sectional area of the laminations. The axial flux is very small because of the high magnetic resistance of air. The axial flux cannot be predicted by analytical methods.

The flux produced by the most important winding faults is of fundamental frequency and the magnitude of its axial component is unforeseeable.

Only for the case of eccentricities in 2-pole machines will the eccentricity field with the number of pole pairs $p - 1$ degenerate to a unipolar flux which successfully can be measured by a ring coil surrounding the stator bore and mounted at one core end.

*With this exception the use of search coils collecting axial fluxes is not recommended.*

### 5.5 Shaft voltage analysis

Some authors allege the usefulness of the measurement of the shaft voltage in order to detect any distortion in the internal flux distribution of a machine.

Shaft voltages are induced by a magnetic ring flux looping around the shaft. This ring flux is caused by irregularities of the stator yoke (e.g. clamping notches) and their distribution along the circumference in case of mains supplied machines. A ring flux is generated only, when the integral of the magnetic field strength around the circumference deviates from zero. The fields with number of pole pairs $p$ and $3p$ play the most important role in this respect. This physical background demonstrates that the impact of winding faults on the shaft voltage is purely parasitic and too small to be used as a sensitive detection device.

In the case of converter supplies, the shaft voltage may considerably increase due to ring flux components, which are caused by the common mode voltage of the converter. Consequently these components of the shaft voltage do not relate to the operational flux distribution of the machine and are totally unsuitable for the intended purpose.

*Summing up, failures at the active parts cannot reliably be detected by an analysis of the shaft voltage.*

## 6 Bearing currents

Bearing currents can be produced by two sources:

- irregularities of the core yoke,
- common mode currents in case of converter supplied motors.

When the yoke contains irregularities such as ventilation ducts, joints, dove-tailed clamping grooves, etc., their number and distribution along the circumference is decisive for the generation of shaft voltages which may result in bearing currents circulating through both bearings. The bearing currents usually contain predominantly the fundamental frequency, superimposed by a component of three-times the fundamental frequency due to saturation effects. Long-standing experience shows that the bearings are endangered when the shaft voltage exceeds 200 mV to 250 mV (r.m.s.). In this case it is the responsibility of the manufacturer to avoid bearing currents by the insulation of the bearing at the non-drive end (NDE). Several kinds of insulation are common.

When the non-drive end bearing is properly insulated, usually no further protection measure is necessary. However, when bridging of the insulation by inadvertent measures cannot be excluded, monitoring of the voltage across the insulation is advisable.

If the rotating machine is supplied by a converter with an impressed d.c. voltage in the intermediate circuit, the common mode voltage (zero-sequence component) of the converter forms an additional source of bearing currents. Depending on details of the configuration, these currents may pass only one bearing (EDM (Electric Discharge Machining) and earth currents flow back to the converter via the grounding system) or they circulate through both bearings, when they are caused by the capacitive currents between the winding and the laminations.

The common mode currents can be measured, but if they can take different paths from the machine frame to the ground, they cannot be taken as indication of the risk. It is the responsibility of the system designer/supplier to decide if the insulation of one bearing is a sufficient precautious measure or if both bearings must be insulated.

The selection of the bearing insulation shall take into account that the frequency of the common mode currents is in the kHz range and that the analysis of the EDM breakdowns comprises much higher values. Capacitive currents cannot be suppressed by a thin insulation film in the range of hundred micrometers.

In case a grounding brush is used, the current flowing through this brush can be analysed in order to find the origin of the current.

A breakdown of the bearing insulation or a discharge through the oil film of the bearings can be monitored by measuring the shaft-to-ground voltage using a sensing brush.

For test purposes contact pins can be installed at both sides of the insulation in order to measure the voltage across the insulation or the bearing current when the insulation is bridged by a strap. Such measurements necessitate the use of appropriate instrumentation and cabling with respect to the high frequencies. Currently, monitoring of these quantities is exceptional.

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