Exploiting Rotor Slotting Harmonics to Determine and Separate Static and Dynamic Air-gap Eccentricity in Induction Machines

M.A. Samonig and Th.M. Wolbank
Vienna University of Technology
Department of Energy Systems and Electrical Drives
Vienna, Austria

Abstract—The paper investigates the influence of pole-pair number on the mixed eccentricity related fault indicators extracted by means of high-frequency or transient signal injection. The method exploits the transient current response to track eccentricity- and slotting-related machine saliencies. By using the fault indicator’s locus, a separation of mixed eccentricity components is performed, without comparison to additional reference measurements of the faultless case (no eccentricity). It is shown, that the fault indicator related to certain machine designs can be used to extract a reliable reference from the eccentric machine. This allows for the separation of static and dynamic proportions from the overall mixed eccentricity.

Keywords—induction machine; transient pulse injection; rotor fault detection; eccentric air gap;

I. INTRODUCTION

An induction machine (IM) consists of many individual machine components. Depending on the industrial application field (automation, traction, railway, etc.) these components may be prone to specific electrical or mechanical system failures [1]. With regard to the present paper, the relevant faults are of mechanical nature and are associated with some sort of misalignment between stator bore and rotor center. This situation is called a rotor or air gap eccentricity and causes a variation in the machine’s air gap length, along the circumference between stator and rotor. Possible sources are either inherent, or develop during operation [2].

A certain degree of inherent eccentricity (up to 10%) is permissible and may be attributed to:

- manufacturing,
- assembly/commissioning.

Additional eccentricities evolve during operation e.g. due to:

- bearing wear or
- unbalanced magnetic pull [3].

These fault related eccentricities may develop into a severe problem. Although no common standard classification does exist, a critical limit is approximately reached at 25-30% for larger (MW) and at about 50% for smaller (kW) machines. At this point, immediate machine shut-down and maintenance is recommended.

Rotor eccentricities may be characterized as a function of space and time. If the rotor is revolving (with progressing time), but the spatial position of the rotor center and thus the minimum radial air gap length are fixed in space, the eccentricity is called static. In this case the rotor center coincides with the center of rotation and is shifted from the stator center, as shown in Fig. 1. Examples causing this kind of fault are: stator core ovality, incorrect stator/rotor assembly or the sum tolerance of individual machine parts [4].

If rotor center and rotational axis are no longer coincident, the eccentricity becomes a dynamic one. In Fig. 1 this condition is characterized by a dashed circle, which is concentric with the stator bore (outer circle). The circle’s center gives the axis of rotation. During one mechanical revolution the rotor center follows the circumference of this circle, whereas the center of rotation is fixed in the middle of the stator bore. Since rotor center and rotational axis are no longer concentric, the position of minimum radial air gap length is spatially moving. This effect may be caused by: non-concentric rotor surfaces, thermal rotor bowing or bearing failures (wear and tear, movement) [4].

Simultaneous occurrence of static and dynamic conditions is denoted by the term mixed eccentricity. As can be seen from Fig. 1 the dynamic (varying) part again is given by a dashed circle, whereas the static (average) part is represented by a horizontal shift of the dashed circle’s center (= center of rotation). In this case the rotational axis is neither aligned with the stator, nor with the rotor center.

Fig. 1.: Representation of static (left), dynamic (middle) and mixed (right) eccentricities, for revolving rotor (black arrow). Dynamic part characterized by dashed circle. Rotor center follows this circle (grey arrow). Static part represented by shifted center of rotation along the horizontal axis.

As summarized in [5], about 50% of all failures in small (kW) machines are related to bearing faults. For large machines (MW) this rate may be reduced significantly down to ~10-15%. However, together with rotor related faults (~10-15%) they...
cause a significant part of breakdowns in small and large machinery. Consequently, reliable IM eccentricity determination is sought after and considerable efforts have been put into scientific research, especially to realize non-invasive detection methods, i.e. without additional sensors.

The majority of methods apply machine current signature analysis (MCSA) to identify sidebands in the stator line-current spectrum related to rotor slotting and/or eccentricity. These sidebands are denoted as low-frequency when located around the fundamental frequency, otherwise as high-frequency. Due to their slot harmonic origin, exploited high-frequency components are greatly influenced by the machine design, i.e. skewing and the relationship between fundamental pole-pair number \( p \) and rotor slot number \( N_{r} \). This dependence has been shown e.g. in [6], [7] and causes detection problems with traditional MCSA. To solve this issue, the authors in [8] explore a detection scheme using the terminal voltage spectrum at IM switch-off. It is concluded that this method works for any machine design.

The paper at hand investigates eccentricity-related effects for another branch of fault detection schemes. These methods rely on the injection of rotating, periodic or transient high frequency signals [9]-[12]. By doing so, stator leakage flux variations caused by machine saliencies (like eccentric air-gaps) can be detected.

The measurements presented were based on transient signal injection, exciting the machine by some 10\(\mu\)s long voltage pulse sequences [12]. The measured transient current response holds the information on the saliency-related transient leakage flux modulations. In [13] this method is compared to traditional MCSA. For each of the investigated designs (2-, 4- and 6-poles, same geometry) at least one harmonic component is identified that is sensitive to eccentricity variations. It is concluded that the method based on transient current response is not affected by \( p \) and \( N_{r} \) design parameters. As also stated, in case of the 6-pole machine the slot harmonic increases with eccentricity fault severity. In [14] authors prove that this eccentricity-dependent effect can also work the other way round, i.e. it may mitigate the rotor slot harmonic down to complete cancelation.

The paper at hand extends the findings of [14] with the focus on eccentricity fault detection. To achieve this, it contributes additional off-line measurement results for the machine designs featured in [13]. In order to interpret these results, they are compared to finite element (FE) simulations. In addition, the comparison is used to assess and improve the FE model. Furthermore, the results allow a quantitative evaluation of the saliency signal magnitudes that may be expected in the presence of eccentricity faults. Especially in case of the mentioned 6-pole machine this gives rise to an additional fault indicator. It will be shown that this indicator contains more information than the mere eccentricity fault severity.

II. Saliency Extraction Method

The machine saliencies are extracted from the machine by evaluating its current response to transient voltage steps. These steps are generated with the drive’s inverter by switching the DC-link voltage at the stator terminals. The transient phase current responses are then measured with the drive’s inherent current sensors.

Due to the step excitation at the stator terminals the squirrel cage is acting as a high-frequency barrier. This prevents the flux from penetrating the rotor yoke. The resulting flux distribution is limited to alternating between stator and rotor tooth tips. Consequently, a high amount of zig-zag leakage flux is generated, making the air gap dominant and linearizing the measured current response. However, the magnetizing currents associated to this transient flux paths are highly dependent on the rotor position, since rotor slot openings (air) are harder to magnetize than rotor teeth (iron). This causes a current slope modulation when the rotor and stator teeth change their relative positions (turning rotor). If the number of rotor slots is \( N_{r} \) and the rotor is turned by one mechanical revolution, the modulation exhibits a periodicity \( n \) equal to \( N_{r} \).

Fig. 2 depicts the saliency signal’s graphical representation for a two pole machine. The dashed circle indicates the trajectory formed by the tip of the current change phasor \( \Delta i_{S} \). Similar trajectories will be investigated in the subsequent chapters and represent the modulating part of \( \Delta i_{S} \), denoted as \( \Delta i_{S,mod} \). The machine saliency (asymmetry) is indicated as ellipse in the left part of, modulating the stator phases’ \( L_{1}, L_{2}, L_{3} \) transient inductances. The constant part \( \Delta i_{S,cont} \) results from the symmetrical machine and represents the average current change rate. The maximum inductance position is given by the mechanical angle \( \gamma \). The electrical angle of the current change phasor trajectory is formed by multiplication with the saliency periodicity factor \( n \).

For a saliency caused by machine saturation this factor equals the number of saturation maxima within the machine. Since only the saturation level and not the flux direction is important, \( n \) equals the pole number \( (2p) \), where \( p \) is the number of pole pairs. This means the tip of the current change phasor rotates \( n = 2p \) times along its trajectory if the saturation is turned by one mechanical revolution.

Of course there exist additional saliencies within the machine. In case of the previously mentioned rotor slotting saliency, the number of trajectory revolutions is \( n = N_{r} \). A rotor eccentricity would cause a signal periodicity of \( n = 1 \). In the following only these two saliencies and their interaction are considered. The test machines are investigated without fundamental wave excitation (no saturation saliency). More information on transient saliency signal extraction can be found in [12].
III. Measurement vs. Simulation

In this chapter, some basic information on the IM designs under investigation, the measurement procedure, and the FE model is given. Thereafter simulations for symmetrical machine (no eccentricity) are compared to measurements and resulting deviations in trajectories are interpreted.

A. Investigated Machine Designs

Three IMs are under investigation. They share the same stator and rotor core geometry, but differ in the number of poles, i.e. have different winding configurations. Corresponding parameters are given in TABLE I where the differences are indicated in bold letters.

<table>
<thead>
<tr>
<th>Table I. Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2p poles</td>
</tr>
<tr>
<td>short-pitching</td>
</tr>
<tr>
<td>Nb/Nr</td>
</tr>
<tr>
<td>rotor</td>
</tr>
<tr>
<td>electrical steel</td>
</tr>
<tr>
<td>nominal air-gap</td>
</tr>
</tbody>
</table>

To guarantee the same transient material behavior, all three machines were manufactured using the same electrical steel (M800-50). However, the air regions prove extremely dominant (flux expulsion into air-gap) during transient pulses without fundamental wave excitation. Therefore, the applied material has negligible influence on the current response as can be seen in [15]. This assumption is valid as long as saturation is absent, which is true for the present investigation.

B. Finite Element model

A detailed explanation of the model approach used may be found in [16]. Summarized, a circuit-coupled 2D FE model is used. The coupled electric circuits model stator and rotor windings. Furthermore, independent voltage source elements apply voltage steps of some 10µs length to the stator terminals. Thus, the simulation is of transient type.

The electrical steel (M800-50) is represented by a linear material model, i.e. a constant permeability is used, similar to the one identified in [15]. As seen later from the comparison of measurement and simulation, this simple approximation is sufficient for the present investigations. It has to be noted that the 3D leakage inductance components (end winding stray field) were not considered by the 2D model at first. To identify their contribution, results from an initial simulation step were compared to the measured leakage inductance. The difference between the corresponding average values (trajectory center in Fig. 2) may be attributed to the absent stray flux components. The difference determined was added to the stator circuit as an additional constant inductance. Finally, a second simulation was started, whose results are in good agreement with measurements. The specific simulation sequence in most parts resembles the measurement procedure presented in the following.

C. Measurement Setup and Procedure

A small scale experimental test stand has been set up, which may be equipped with the machines of Table I. The voltage step sequences are generated by a voltage source inverter with 440V DC-link voltage. The current response in each stator phase is measured by three individual current sensors. A variable speed AC machine is linked to the rotor shaft and serves as a drive unit. The control and measurement system is realized by a computer system programmable under MATLAB/Simulink. The corresponding block diagram is given in Fig. 4.

![Block diagram: data acquisition and fault indicator calculation.](image)

The measured (fine lines) and simulated (thick line) current change trajectories for 2-pole machine. Same scaling as in Fig. 3.
During a measurement sequence the test machine rotor is slowly turned at about 0.01 p.u. while the inverter is continuously generating the test sequences. Consequently, the generated test voltage phasor slowly scans the machine saliencies. The sampled current derivative values are collected in a matrix, where each row represents a specific rotor position. The angular resolution of one mechanical revolution was thereby fixed to 256 steps. To reduce measurement noise 100 single measurements were averaged for each of these 256 rotor positions. The resulting current change trajectories are compared to simulations in the next section.

D. Comparing Measurement and Simulation

The simulations in this chapter were done with concentric rotor (no eccentricity) and the results are compared to measurements for the corresponding test machines. As mentioned in section I, inherent eccentricity saliencies can be expected along the standard slotting saliency. Indeed, these effects can be identified from the measurement results (thin blue lines) in Fig. 3 and Fig. 5. The prominent saliency effect is related to the rotor slotting, though. According to the notation used in Fig. 2 its periodicity is $n = 28$ and causes 28 circular trajectory revolutions.

Especially for the machines with 2 and 6 poles the eccentricity effect can be observed nicely and moves the trajectory along the real axis. The eccentricity-related movement along the real axis starts from the center of the simulated trajectories (red trajectories, thick-dashed lines) and again reaches this point after one mechanical revolution. Corresponding to the notation in Fig. 2 this means a periodicity of $n = 1$. This period is not visible for the 4-pole machine, which only exhibits the 28 slotting revolutions. Therefore, it may be concluded that this machine is the most centric one.

In case of 2- and 4-pole machine, measurement and simulation show good agreement of the trajectory diameter and form. A slightly oval form (stretching in direction of imaginary axis) is visible for 4 poles, though. This is due to an additional counter rotating -28th slotting harmonic. A possible explanation are transient magnetization effects that cause an imbalance between the rotor teeth, which is not considered by the FE model.

Especially the centers of the simulated trajectories are coincident with the measured minimum eccentricity position. This exact match is due to the way the average leakage inductance has been adjusted to consider the end winding stray flux (also see section III.B). During the trajectory movement, the point of minimum eccentricity (maximum air-gap influence) gives the maximum current change response. The corresponding rotor position is the most centric one and has been used to estimate the end winding inductance according to section III.B. However, for the 2- and 4-pole machine it is not the actual point of centric rotor. Since the simulation assumes a completely centric rotor, this introduces an offset in the static eccentricity value. This error cannot be compensated without reference measurements conducted on a symmetric machine. Therefore, the simulation results are used in the following only to give a qualitative view on the eccentricity behavior in the 2- and 4-pole machine. As will be seen later, this approximation gets much more accurate in case of the machine with 6 poles.

The trajectory of the 6-pole machine Fig. 3 (left) is showing an additional modulation of the trajectory diameter. In other words, the magnitude of the rotor slotting harmonic is dependent on the eccentricity level. This is indicated by the dotted lines approximately enveloping the trajectory course. The intersection of this envelope functions equals the centric rotor condition (red point), as modelled by the simulation. More information on this effect is given in [14]. It is used in section IV.C to estimate the proportion of static and dynamic eccentricity. Based on further simulations the next chapter aims at discussing the mixed eccentricity effects manifesting in the measurements of Fig. 3 and Fig. 5.

IV. DISCUSSION

A. 2-pole machine

The start of this discussion is made by the 2-pole machine. However, differing from the centric simulation (Fig. 5) an additional mixed eccentricity has been added to the FE model. Eccentricity severity has been increased until the resulting trajectory movement showed good agreement to the measurements. The result is depicted in Fig. 6 and shows a trajectory movement similar to the measurements of Fig. 5. Following the average movement of the trajectory in Fig. 5 reveals that its center is moving along an ellipse. As will be seen, when comparing the results to the other pole numbers, this elliptic signature is specific for the 2-pole case. From the comparison it may be concluded that a mixed eccentricity is present in the test machine, which is equivalent to approximately 10-15% static and dynamic share each. However, as mentioned previously in case of this machine an estimation of eccentricity (especially static) is prone to inaccuracy, since no reference of an ideal centric rotor condition does exist. It was only assumed that the point of minimum eccentricity in Fig. 5 is equal to a centric rotor position in the test machine. The dynamic part, that actually causes the trajectory movement, is very likely to be in the estimated range, though.

Fig. 6: Simulation results for 2-pole machine: 30% mixed (fine lines) and 0% (thick line) eccentricity. Equal share of static and dynamic parts, (15%) each. This gives 30% at the most eccentric rotor position. Ellipse indicates the movement of the trajectory center.
B. 4-pole machine

In the previous chapter it has already been stated that the measurement results for the 4-pole machine suggest a very centric rotor position. In fact, the bearing shields for this machine were altered to counter any static eccentricity. Since the trajectory in Fig. 5 is not moving, the absence of dynamic eccentricity is very likely, too. To give an example what such a movement could look like, a simulation with 50% mixed eccentricity (15% each, static and dynamic) was conducted. The results are given in Fig. 7. (right). The simulations were done with a reduced angular resolution. Therefore, the trajectory course is not as smooth as in the previous simulations. Compared to Fig. 5 (2-pole machine with elliptical movement) the trajectory center is now only moving along the real axis and shows no eccentricity-dependent displacement along the imaginary axis. Consequently, the resulting signature form of the 4-pole machine is a straight line here. Same conclusions about the accuracy of static and dynamic eccentricity estimation are true as for the 2-pole machine. Accuracy can only be increased if reference measurements of the centric rotor are conducted.

C. 6-pole machine

In case of the 6-pole machine (Fig. 7) the simulation with 50% mixed eccentricity shows a trajectory movement very similar to the measurements in Fig. 3. This movement features dominantly a horizontal displacement and an additional change in the slotting modulation’s magnitude. From this alone the machine is not distinguishable from the 4-pole machine. However, as already seen from the measurements an additional modulation of the rotor slotting saliency signal is present in the case. The modulating trajectory diameter therefore may be exploited as additional eccentricity indicator and gives the trajectory its specific signature form.

Furthermore, the simulation confirms that the enveloping functions of this modulation meet at the point of centric rotor condition. Thus, they may theoretically be exploited to estimate the symmetric reference condition (with centric rotor) from the measurements. An additional reference measurement of the symmetric machine is thus not needed. The accuracy of this estimation is directly linked to the approximation of the enveloping function. More comprehensive investigations on this topic are currently scheduled.

For now, the envelope is only graphically approximated by linear functions as indicated in Fig. 3 and Fig. 7 from which the centric rotor condition is reconstructed. What does this mean for the possibility to separate static and dynamic eccentricity component from each other? This question is answered with the help of Fig. 8.

Mathematically, the share of two unknown parameters, which are proportional to the maximum occurring eccentricity, is to be found. In the special case of the 6-pole machine now two eccentricity indicators may be exploited to achieve this. If the point of centric rotor is known (black, filled dot in) this means that also the share of the individual components can be determined. In Fig. 8 the static part is indicated by the red (x) marker and is obtained as the average value of horizontal movement of the slotting modulation’s midpoint. This movement is indicated by the two positions marked ○. The distance between the average value (x) and these markers (○) represents the dynamic part. The sum of the two parts, static eccentricity (distance between average value (x) and symmetrical case (●)) and dynamic eccentricity (distance between (x) and (○)), equals the maximum eccentricity.

Thus, static and dynamic proportions can be identified from Fig. 8 and contribute 2/3 and 1/3 to the maximum eccentricity, respectively. It has to be stressed, that the actual maximum eccentricity value, i.e. its overall severity, in percent of the nominal air-gap length (TABLE I), is not needed to separate the two eccentricity proportions.

Fig. 7: Simulation results for 6-pole (left) and 4-pole (right) machine: 50% mixed (fine lines) and 0% (thick line) eccentricity. Equal share of static and dynamic parts, (25%) each. This gives 50%, respectively, at the most eccentric rotor position. Arrows indicate the trajectory movement/modulation.

Another example of this procedure is given in Fig. 9. Since the results are taken from simulations, the overall eccentricity severity as well as the two components are known exactly (50% overall, 25% static, 25% dynamic – percentages are given with respect to the nominal air-gap length). Following the presented separation procedure, it is found that static and dynamic parts each share half of the overall eccentricity value. Since both
shares are equally distributed, the dynamic part cancels out the static eccentricity at one point of the rotor movement. In fact, this is the point where the slotting modulation vanishes (centric rotor).

Fig. 9: Simulation results for 25% static and 25% dynamic eccentricity (max. eccentricity is 50% of nominal air-gap length).

V. CONCLUSION

The influence of pole-pair number on eccentricity related fault indicators has been discussed for a transient signal injection method. The method exploits the transient current response to track eccentricity- and slotting-related machine saliencies. By using the fault indicator’s locus, an evaluation of mixed eccentricity and its separation has been proposed. This was done without the need for reference measurements of the symmetric case (no eccentricity), by exploiting information contained in measurements of the faulty (eccentric) machine alone. The following conclusion can be drawn for the investigated 2-, 4- and 6-pole machines.

- The pole-pair number causes specific movement of the fault indicator locus. This suggests that these signature of the locus can be used to identify the unknown pole number of a machine, as long as a mixed eccentricity is present.

- In case of 2- and 4-poles only a single eccentricity indicator can be identified in the machine current response. Therefore, separation of static and dynamic share is not possible without reference measurement on a symmetrical machine.

- The 6-pole machine is special, since it exhibits two separate fault indicators. This allows for reconstruction of the symmetric machine locus of similar machines in the presence of mixed eccentricity. With this additional information, the static and dynamic eccentricity share can be estimated with good accuracy.

In order to further confirm these findings additional investigations on a test stand, allowing systematic alteration and measurement of static and dynamic eccentricity, are planned. The technique presented in this paper is applicable for machine tests at start-up. With regard to its on-line applicability the influence of saturation effects on the eccentricity fault indicator is of particular interest and needs to be addressed in future investigations.

REFERENCES