EFFECTS OF ECCENTRICITIES ON SHAFT SIGNALS STUDIED THROUGH WINDINGLESS ROTORS

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Abstract: Shaft signals of electric rotating machines offer potentials for defect detections. The signals are affected by many factors. This study specifically focuses on how eccentricities affect shaft signals through theoretical predictions and tests conducted on windingless rotors. Windingless rotors imply currentless rotors. For symmetrical synchronous machines running at steady synchronous speeds, the induced rotor currents are zero while harmonics are neglected. One advantage in experiments for this study is that air gaps can be shimmed accurately at standstill without end brackets; certain tests can be conducted at standstill without facing unmanageable locked-rotor currents for the test machines.

Shaft signals decrease when the rotor of a machine closely situates at the center of stator bore. Shaft signals increase under greater eccentricities when stator and rotor axes are parallel. Tilted rotors reduce shaft signals.

Even when there are no rotor windings, inherent positional characteristic exists. This characteristic produces cyclic shaft-signal components that are related to rotor revolutions.

I. INTRODUCTION

Dynamic air gap monitoring is fairly recent activity conducted by utility companies [1]. Pollock and Lyles report the successful use of capacitive air gap monitors for vertical hydrogenerators. In the discussion section of their paper, Toom and Talas present the use of fiber optic monitors for the same purpose. It appears that satisfactory results can be obtained through either capacitive or fiber optic methods. The sensors have to be mounted inside machines.

Cameron, Thomson, and Dow [2] discuss vibration and current monitoring for detecting air gap eccentricity in large induction motors. Neither mountings inside machines, nor shaft currents are involved in that study.

Marques Cardoso et. al. [3] present their experimental study of on-line detections of air gap eccentricity in 3-phase

induction motors by Park's vector. Again, no shaft currents or mountings inside machines are involved. The locus of the vector changes from a sharply focused circular trace to a locus with certain blurs while eccentricity occurs.

The existence of shaft currents that sometimes flow through uninsulated bearings of electric machines and cause damages is well known. In order to bypass shaft currents, grounding brushes are commonly used for turbogenerators. For large induction and synchronous machines, insulating all bearings except the driving-end bearing and using insulated couplings for dual-extension shafts are common practices for preventing shaft currents.

Alger and Samson [4] point out three major causes of shaft currents. They are: 1) direct or alternating flux flowing in the shaft that produces homopolar voltages, 2) difference of potential between shaft and ground due to electrostatic effects, and 3) alternating flux linking the shaft. It is also suggested in [4] that the most prominent causes of asymmetries are sectional frames and segmental punchings. The shaft current frequency is basically fundamental with harmonics that are related to the numbers of joints of punchings. The shaft currents produced by eccentricities are not included in their study.

Verma and Girgis [5] suggest that magnetic asymmetries such as rotor eccentricity, rotor sagging, the use of segmental punchings, shorted field turns, and asymmetrical loadings are causes of shaft voltages. The magnitude of shaft voltage is generally larger for larger machines. Important frequency components are the fundamental frequency, the third, the fifth, and the seventh harmonics.

Meyer et. al. [6] describe a (Resistor-Capacitor) RC-grounding device that reduces the high frequency spikes caused by the static excitation system. Ammann, Reichert, and Posedal [7] report their operating experience with RC-grounding device and the possibilities for monitoring the condition of turbogenerators. The second and sixth harmonics in shaft voltages are linked respectively to the dynamic eccentricity and to the asymmetries in the excitation circuit.

It is generally agreeable that any stator, rotor, air gap structural, or magnetic asymmetry in a rotating machine may alter flux paths to have a portion of the flux encircling the shaft to generate ac voltages. Homopolar voltages can also be generated when the shaft carries flux with a magnetic returning path directly from the shaft to the stator. Regardless of the differences between synchronous and asynchronous machines, there are certain basic factors that affect magnetically induced shaft voltages.

Besides what has been discussed in the existing literatures, this study specifically focuses on how eccentricities affect shaft signals through theoretical predictions and tests conducted on windingless rotors. One advantage in experiments for this study is that air gaps can be shimmed accurately at standstill without end brackets; certain tests can be conducted at standstill without facing unmanageable locked-rotor currents for the test machines.

Shaft signals decrease when the rotor of a machine closely situates at the center of its stator bore. The shaft signals increase under greater eccentricities when stator and rotor axes are parallel. Tilted rotors reduce shaft signals due to opposite shaft flux linkages at both ends.

Parallel connections of stator windings significantly reduce the shaft voltages and shaft flux linkages. Inherent positional characteristic exists even when there are no rotor windings. This characteristic produces cyclic shaft-signal components that are related to rotor revolutions.

Similar studies on other types of structures will be useful. However, the fundamental knowledge obtained in this study helps to understand the shaft voltages of other structures.

Further studies on uses of shaft voltages for monitoring eccentricities, rotor-to-stator rubbings, rotor shorted turns, and stator shorted turns of actual electrical machines are being carried out.

II. SHAFT VOLTAGES CAUSED BY ECCENTRICITIES UNDER SERIES STATOR WINDINGS

This section discusses the simplest situation that shaft voltages caused by eccentricities of rotating machines are under series stator windings.

A. Air-Gap Magnetomotive Force and Flux Components

When a three-phase rotating machine, having sinusoidally distributed, series connected, symmetrical windings, is fed with balanced fundamental-frequency, multi-phase currents, a sinusoidally distributed magnetomotive force (MMF) rotating at synchronous speed is generated. Assuming the infinitely permeable characteristic of ferromagnetic materials, the rotating sinusoidal MMF is accountable only for the air gaps. Because the stator winding is connected in series, the excitation MMF's for individual poles are the same. Regardless of the air gap variations the amplitude of air gap MMF remains uniform.

$$\text{MMF} = F \cdot \sin(p \cdot \vartheta - \omega_s \cdot t) \quad (1)$$

where,

F = Amplitude of MMF

p = Number of pole pairs

ϑ = Angular position of rotor in mechanical radian

$$\omega_s = 2\pi f$$

f = Terminal frequency in hertz

t = Time in seconds

The air gap flux density is proportional to the ratio of air gap MMF over air gap length. Even with an air gap MMF of uniform amplitude, the variations of air gap length caused by eccentricities, slot openings, salient pole faces, and etc. produce a nonsinusoidal air gap flux. Its frequency is basically fundamental but with harmonics.

More harmonic fluxes would be produced when stator windings are fed with unbalanced phase currents that produce negative-sequence rotating fields, or when magnetic saturations occur.

B. Experimental Setups

The setups are designed to provide maximum possible alternative combinations from the minimum parts required. A 5-hp, 3-phase, 4-pole, 230/460v, YY/Y-connected, induction motor is used as the basic machine. Two rotors, made of 0.559 mm, non-oriented, 0.35% Silicon steel laminations, without any windings or cages are obtained from manufacturer. The rotor core length is 12.7 cm and the diameter is 11.4 cm. A digital torque gauge and speedometer are coupled to the machine being tested.

For a test, individual end brackets may be selected from different sets that include the original sets and various off-center sets. The bore diameters inside the bearing housings of one set of the end brackets are enlarged to accommodate the original ball bearings wrapped with two layers of kapton® tapes for insulation purposes. However, it was tested that for small NEMA-frame machines, the oil films of bearings serve as sufficient insulation. The flange diameters of the end brackets of this set are machined off a small amount to enable adjustments of eccentricities. The radial positions of the end brackets are not held by the conventional tight fits of flanges, but rather by tightening the axial bolts that press the end brackets to the stator frame. Because the eccentricities of air gaps cannot be duplicated after the machine is disassembled, comparisons for tests with rotating rotors are made to their greatest extends under the same assemblies for consistent eccentricities.

Shaft voltages are collected through copper wires riding on the nondriving end and on the surface of the driving end of shaft. The same signal is also used as the input of a resistor-capacitor integrator ($R=33 \text{ k}\Omega$, $C=0.165 \mu\text{F}$) as shown in fig. 1. The impedance at 60 Hz is $33 \cdot 10^3 - j16.1 \cdot 10^3 \Omega$. From the frequency response standpoint, it gives an approximate indication of the flux linkages corresponding to the shaft voltages.

C. Shaft Voltages Caused by Static Eccentricities Under Series Stator Windings

Fig. 2a shows the side view of an eccentric location of rotor; the stator axis is in parallel with the rotor axis. Series stator windings produce a rotating MMF of uniform amplitudes. The smaller gap yields more air gap flux. Fig. 2b shows fluxes of a 4-pole machine. Permeabilities of rotor ferromagnetic materials are finite; more unbalanced air gap flux pushes the flux inside the rotor core to the opposite side of shaft. Consequently, the unbalanced flux is linked with the shaft. Since the field produced by stator currents is rotat-

Fig. 1. A simple resistor-capacitor integrator ($R=33\text{ k}\Omega$, $C=0.165\text{ }\mu\text{F}$)

Fig. 2. a) Side view of an eccentric rotor location
b) Shaft Flux linkages with respect to air gap rotating fluxes

ing, the flux linkage [9] to the shaft is alternating. The major frequency of induced shaft voltage is the fundamental frequency.

The upper trace of fig. 3 shows the shaft voltage of a 3-phase, 5-hp, 4-pole machine with series stator windings but without rotor winding (or cage). The total air gap of both sides is approximately 0.508 mm. A certain eccentricity exists with slightly off-center end brackets. The rotor is running at 133 rpm while the stator is fed with 60 Hz currents. The shaft voltage of a running rotor reflects static and dynamic eccentricities as well as a positional characteristic that is discussed in the next section. The lower trace corresponds to the shaft flux linkage through a resistor-capacitor (RC) integrator. Major time duration between adjacent peaks of the wave envelopes is the time duration of one shaft revolution. Careful examination of fig. 3 shows that a waveform within one revolution is not exactly identical to waveforms within adjacent revolutions. This is going to be discussed further in the section of "further evaluations of rotor inherent positional characteristics".

The horizontally expanded traces at 133 rpm of fig. 3 are shown in fig. 4. The major frequency of the induced shaft voltage is the fundamental terminal frequency. The adjacent waveforms per cycle are different from each other.

D. Rotor Inherent Positional Characteristics Under Series Stator Winding

The variation of shaft signals per revolution is partly caused by rotor inherent positional characteristics that reflect the differences in flux paths and manufacturing tolerances, such as the slightly asymmetrical flarings of stator and rotor lamination stacks, the off-center tolerances of the rotor punchings, the nonidentical rotor slot bridges, the stray shorted circuits of rotor cores and other miscellaneous asymmetries.

Rotor asymmetries with respect to its magnetic-path positions can be expressed in terms of harmonic components. The lowest harmonic order component is proportional to $\sin(\vartheta)$. This means that one-half of the rotor reacts differently from its opposite half.

The same rotor used for previous tests that has 44 rotor slots and 8 axial rotor ventilation ducts is in the test motor. From visual examination, the rotor appears to be perfectly symmetrical.

The stationary rotor tests that reflect the static eccentricity and the positional characteristic are conducted without disassembling the machine. This keeps the same eccentricity

Fig. 3. Data taken from a 3-phase, 4-pole machine with series-Y stator windings but without rotor winding (or cage) at 133 rpm while the stator is fed with 90 V per phase, 60 Hz currents. Upper trace: shaft voltage (30 mV/div.). Lower trace: shaft flux linkage through RC integrator (20 mV/div.). Horizontal scale: (100 mS/div.)

Fig. 4. Horizontally expanded traces at 133 rpm of fig. 3. Upper trace: shaft voltage (30 mV/div.). Lower trace: shaft flux linkage through RC integrator (20 mV/div.). Horizontal scale: (5 mS/div.)

ty as that for the previous tests. Figure 5a shows the maximum shaft voltage and shaft flux linkage selected by gradually shifting the rotor locations. Under the same terminal voltages, fig. 5b shows the shaft voltage and flux linkage while the rotor location is shifted 90 mechanical degrees from the maximum location. It is noted that the magnitudes of the shaft voltages or flux linkages are approximately the same regardless of whether the rotor is running or at a standstill when there is no rotor windings. The differences between running and standstill are: 1) When the rotor is stationary, there is no dynamic eccentricity and the rotor positional characteristic is reflected within each cycle; the adjacent waveforms per cycle are the same as each other. 2) The traces of both shaft voltages and shaft flux linkages contain only odd order harmonics.

A motor identical to the 4-pole experimental machine is rewound for a 6-pole machine. Rotors can be exchanged between the 4-pole and this machine. With reference to fig's. 5a and 5b of a 4-pole machine, fig's. 6a and 6b show the corresponding traces of a 6-pole machine. The shaft voltage does not show any significant ripples corresponding to the slot openings. The basic frequency of the traces at phase voltage of 100 V is 60 Hz of the supply frequency with certain odd harmonics. It is shown later that when the machine is operated under saturated conditions, harmonic contents go up significantly.

III. SHAFT VOLTAGES CAUSED BY ECCENTRICITIES UNDER PARALLEL STATOR WINDING

Parallel stator windings have tendencies to balance asymmetrical air-gap fluxes. When air gap fluxes are not linked equally to each individual winding connected in parallel, there are circulating currents flowing among windings to equalize the total fluxes for individual windings. Windings corresponding to bigger air gaps takes more current for excitation. Subsequently, the higher current has a greater leakage reactance voltage drop, and the back induced voltages from the air-gap fluxes in the individual parallel circuits are not the same. This explains why the air gap flux is not absolutely balanced with parallel windings. However, especially under nonsaturated conditions, it is reasonable to expect that the shaft voltages are lower than those of motors with series windings.

The machines for tests have parallel (YY) stator windings, which are the only differences from those used for the previous tests with series (Y) windings. Again, the rotor does not have any winding or cage.

A. Reductions of Shaft Voltages and Shaft Flux Linkages Under Parallel Windings

Fig. 7 shows traces of the same 4-pole machine with parallel windings. The terminal connection is changed from series Y to parallel YY. The rotor runs at 130 rpm. The same eccentricity as that for series windings is kept without disassembling the machine. In order to maintain approximately the same air gap flux, the terminal voltage is reduced to about half (46 V) of the value (90 V) used previously.

The magnitudes of both the shaft voltage (upper trace) and the shaft flux linkage (lower trace) are significantly

reduced from those shown in fig. 3 of the series windings. Again, the time duration between adjacent peaks of the wave envelopes is equal to the time duration of one shaft revolution.

Fig. 5. Effects of rotor inherent positional property obtained through stationary rotor tests at 60 Hz and 90 V per phase of a 4-pole, series stator winding machine. Horizontal scale (5 mS/div.)
5a. Upper trace: Maximum shaft voltage (30 mV/div.); Lower trace: Shaft flux linkage (20 mV/div.)
5b. Rotor is shifted 90 mechanical degrees from the maximum location. Upper trace: shaft voltage (30 mV/div.); Lower trace: shaft flux linkage (20 mV/div.)

Fig. 6. Effects of rotor inherent positional property through stationary rotor tests at 60 Hz and 100 V per phase of a 6-pole machine. Horizontal scale: (10 mS/div.)
6a. Upper trace: maximum shaft voltage (30 mV/div.); Lower trace: maximum shaft flux linkage (20 mV/div.)
6b. Rotor is shifted 90 mechanical degrees from the maximum location. Upper trace: shaft voltage (30 mV/div.); Lower trace: shaft flux linkage (20 mV/div.)

Fig. 7. Data taken from a 3-phase, 4-pole machine with parallel (YY) stator windings but without rotor winding (or cage) at 133 rpm while the stator is fed with 46 V per phase, 60 Hz currents. Upper trace: shaft voltage (30 mV/div.); Lower trace: shaft flux linkage through RC integrator (20 mV/div.); Horizontal scale: (100 mS/div.)

tion. The envelop indicates the effects of rotor inherent positional characteristics, as well as the static and dynamic eccentricities of a running rotor.

The stationary rotor tests are conducted without disassembling the machine. Fig. 8a shows the maximum shaft voltage and shaft flux linkage. Under the same terminal voltage (46V), fig. 8b shows the shaft voltage and flux linkage while the rotor location is shifted 90 mechanical degrees from the maximum location. The change of waveforms from series to parallel connections can be seen by comparing fig's. 8a and 8b with 5a and 5b. The harmonic portions are less suppressed than the fundamental component while parallel connections are used. Again, when the rotor is stationary, the rotor positional characteristic is reflected in each cycle, the traces of both shaft voltages and shaft flux linkages contain only odd order harmonics.

B. Further Evaluations of Rotor Inherent Positional Characteristics

In order to examine whether the rotor inherent positional characteristics are general phenomena, a second laminated, slotted, cylindrical rotor without rotor winding that also appears to be symmetrical from visual examination is used. Again, as it is shown under the series stator winding situation, a similar positional characteristic is observed under the parallel winding situation. Fig. 9 shows the traces of shaft voltages and shaft flux linkages when the stationary rotor is increased 60 mechanical degrees for each step. The stator parallel winding is fed with 60-Hz, 3-phase voltages at 71 V per phase. The windingless rotor is assembled with a fixed eccentricity. Corresponding to the shift of rotor angular positions, the changes of trace patterns and the slight variations of excitation currents (not shown) further confirm the inherent positional characteristics of rotors.

It has been discussed that the envelope period of shaft signals equals the period for a revolution. This is true for coarse estimations. Further details of inherent positional characteristic are discussed through the following example.

Fig. 10 shows shaft-flux-linkage signals of a 4-pole motor with a cageless laminated rotor at 950 rpm, 60 Hz, and 230 V. The synchronous speed is 1,800 rpm. Substituting into equation (2)

Fig. 8. Effects of rotor inherent positional property through stationary rotor tests at 60 Hz and 46 V per phase of a 4-pole, parallel stator winding machine. Horizontal scale: (5mS/div.)

8a. Upper trace: maximum shaft voltage (30 mV/div.); Lower trace: maximum shaft flux linkage (20 mV/div.)

8b. Rotor is shifted 90 mechanical degrees from the maximum location. Upper trace: shaft voltage (30 mV/div.); Lower trace: shaft flux linkage (20 mV/div.)

Fig. 9. Rotor inherent positional property shown through shaft voltages and shaft flux linkages tested at 60 Hz with 71 V per phase. Rotor positions: a_0°, b_60°, c_120°, d_180°, e_240°, f_300°, g_360° (mech. degrees). Upper trace: shaft voltage (60 mV/div.). Lower trace: shaft flux linkage (20 mV/div.); Horizontal scale: (5 mS/div.)

No. of fundamental cycles per revolution

$$= \frac{(\text{Syn. speed})}{(\text{actual speed})} \cdot \left(\frac{\text{No. of Fund. cycles per}}{\text{synchronous revolution}} \right) \quad (2)$$

gives the number of fundamental cycles per revolution:

$$\frac{1,800 \text{ rpm}}{950 \text{ rpm}} \cdot 2 [\text{Fund. cycles}] = 3.79 [\text{Fund. cycles}]$$

For a revolution starting at an initial point of the rotating flux that is assumed to contain only the fundamental, forward-rotating flux, a given pattern of shaft flux linkages is generated. The same pattern is not necessary to repeat at the next revolution, because the phase angle of stator MMF may change from that of the original initial point.

In order to repeat the initial point of stator MMF at the beginning of m revolutions, the following equation holds:

$$m \cdot (\text{No. of fund. cycles per revolution}) = \text{Integer} \quad (3)$$

The product of left-hand-side of (3) must be an integer. The lowest possible value that the product of $m \times 3.79$ of the example closes to an integer is when $m=5$:

Fig. 10 confirms (3) that the pattern repeats itself roughly every 19 fundamental cycles.

m	1	2	3	4	5	6
$m \times 3.79$	3.79	7.58	11.37	15.16	18.95	22.74

C. Effects of Eccentricities, Saturations, and Rotor Vent Ducts

This section clearly shows that when eccentricity increases, shaft signals go up. The 4-pole, parallel stator winding machine used for previous tests is disassembled. The windingless, laminated, cylindrical, slotted rotor is wrapped with several layers of masking tape and inserted into the stator bore for the nearly centered location. For balancing off the small gap between the masking tape and the stator bore that is required for the rotor insertion, radial force is asserted downward by hand to one end of the shaft. The rotor is slightly tilted as shown in fig. 11. The total air gap (both sides) of this set up is approximately 0.508 mm measured by a feeler gauge. The left hand column of fig. 12 shows the traces of this nearly centered and slightly tilted position. The middle column of fig. 12 is for the parallel eccentricity location with the shimmed rotor resting on a 0.051 mm paper inside the stator bore. The right hand side column is for the same rotor location with the rotor rotated 90 mechanical degrees from the rotor position of the middle column.

In order to investigate the effects of saturations through examples, the phase voltages applied to the 3-phase stator windings are stepped up from 45, to 75, to 100, and finally to 133 volts. Their corresponding traces are shown from the first line of fig. 12 toward the bottom line.

The summary of fig. 12 is:

1) Comparing the traces of column one with those of

columns two and three, it clearly shows that the magnitudes of both shaft voltages and shaft flux linkages are consistently lower for the nearly centered and slightly tilted location (column one) that has less eccentricity than those of the others.

2) The trace magnitudes corresponding to the nearly centered position are small. The changes of magnitudes at various rotor angular positions are relatively insignificant as compared with those shown in columns 2 and 3 for the high eccentricity positions. This indicates that the rotor inherent positional characteristic is more significant when it is associated with higher eccentricities.

3) Looking at the traces from the top of fig. 12 toward the bottom, it reveals when the terminal voltage goes up both the shaft voltages and the shaft flux linkages increasingly show the contents of more harmonics. The first line of traces is taken at 45 V, which corresponds to a nonsaturated situation. The traces have more fundamental components. The second line is taken at 75 V that refers to a higher flux density situation than that of the 45 volts. The third harmonic components are significant. This fig. also shows that as the saturation level goes up, the fifth harmonics shown in the traces of the third line increase, and the seventh harmonics shown in the traces of the bottom line become significant. Besides the fact that the flux distributions become more non-sinusoidal under saturation conditions, the eight ventilation holes in the rotor certainly affect the saturation situation. In other words, the structures of machines affect the specific shapes of traces, but the general trend shown here remains valid.

4) The traces of the third and the fourth lines show that the magnitudes of the shaft voltage and/or shaft flux linkage

Fig. 10. Shaft-Flux-linkage signals of a 4-pole induction motor with a cageless laminated rotor at 60 hz, 230 V, and 950 rpm (phase currents: 4.7/4.6/5.1A)

Fig. 11. A nearly centered and slightly tilted rotor at standstill

Fig. 12. Shaft voltages and shaft flux linkages under various eccentricities and saturation levels. Top traces are for shaft voltages (60 mV/div.); Bottom traces represent shaft flux linkages (20 mV/div.); Horizontal scale: (5 mS/div.)

Columns of traces from left to right: 1) rotor at nearly centered and tilted position. (a1, b1, c1, d1); 2) rotor at parallel eccentricity location with rotor shimmed and resting on a 0.051 mm paper inside the stator bore. (a2, b2, c2, d2); 3) rotor at same location as 2, but is turned 90 degrees from above. (a3, b3, c3, d3); Lines of traces from top to bottom: a) phase voltage = 45 V (a1, a2, a3, b); b) phase voltage = 75 V (b1, b2, b3); c) phase voltage = 100 V (c1, c2, c3); d) phase voltage = 133 V (d1, d2, d3)

are not necessarily going up while the terminal voltage goes up. Instead, the trend is that higher orders of harmonics occur.

5) The symmetries of the traces suggest that only odd orders of harmonics exist. This is in line with what was said previously, that when rotor is stationary and without rotor currents, the rotor positional characteristic does not come in as time varying factors, the traces of both shaft voltages and shaft flux linkages contain only odd order harmonics.

D. Shaft Voltages and Shaft Flux Linkages at Speeds Close or Equal to Synchronous Speeds

Referring to fig. 4 or 8, the rotor inherent positional characteristic makes the variations of shaft voltage and shaft flux linkage roughly repeat every single revolution. When the speed goes up to a speed close to or at synchronous speed, the time period for such a variation is close or equal to p times the supply-frequency period.

The lowest-order component of inherent positional characteristic can be expressed through,

$$(1 + k_1 \cdot \sin \vartheta). \quad (4)$$

The value of (4) increases at half of the rotor location per revolution but reduces at the other half of the rotor location. The coefficient represents the significance of the rotor posi-

tional characteristic. When running at a speed close or equal to the synchronous speed, the time period of one revolution is close or equal to p times the supply-frequency period, the value of ϑ can be approximately written as,

$$\vartheta \approx \frac{\omega_s \cdot t}{p} \quad (5)$$

Substituting (5) into (4) gives,

$$(1 + k_1 \cdot \sin \vartheta) \approx \left(1 + k_1 \cdot \sin \frac{\omega_s \cdot t}{p} \right) \quad (6)$$

When motors run at a speed close or equal to the synchronous speed with eccentricities under nonsaturated situations, the shaft flux linkage of one revolution is proportional to the product of the positional characteristic function of (6) and the supply-frequency shaft flux linkage. This relationship can be presented as follows:

$$\text{shaft voltage} \propto \sin(\omega_s \cdot t) \cdot \left(1 + k_1 \cdot \sin \frac{\omega_s \cdot t}{p} \right) \quad (7)$$

Simplifying equation (7) gives,

$$\begin{aligned} \text{shaft voltage} &\propto \sin(2 \cdot \pi \cdot f \cdot t) \\ &+ \frac{k_1}{2} \cdot \cos \left[2 \cdot \pi \cdot \left(1 - \frac{1}{p} \right) \cdot f \cdot t \right] \\ &- \frac{k_1}{2} \cdot \cos \left[2 \cdot \pi \cdot \left(1 + \frac{1}{p} \right) \cdot f \cdot t \right] \end{aligned} \quad (8)$$

From equation (8), under nonsaturated situation, because of rotor inherent positional characteristics, the shaft voltage or flux linkage contains three major frequencies. They are: f , $(1-1/p)f$, and $(1+1/p)f$. For example, the shaft voltage of a 4-pole ($p=2$), 60 Hz ($f=60$) machine is most likely to contain 60, 30, and 90 Hz waves. Fig. 13 shows the shaft voltage and shaft flux linkage of a 4-pole machine that has a parallel stator winding and a windingless, laminated, cylindrical, slotted rotor. The time period corresponding to each revolu-

Fig. 13. Shaft voltage and shaft flux linkage of a 4-pole machine with parallel stator winding and a windingless, laminated, cylindrical, slotted rotor at 70 V per phase. The rotor is driven at 1,798 rpm. The time period corresponding to each revolution is marked. Upper trace: shaft voltage (20 mV/div.); Lower trace: shaft flux linkage (10 mV/div.); Horizontal scale: (10 mS/div.)

tion is marked. For the lower trace of flux linkages, the basic frequency is 60 Hz. The higher magnitudes at the beginnings and the ends of each period suggest the existence of a 30 Hz component.

IV. CONCLUSIONS

Shaft signals of electric rotating machines reflect asymmetrical situations that relate to defects. Therefore, studies on shaft signals enhance technological potentials for defect detections. Theoretical predictions and extensive tests are included in this investigation.

One advantage in experiments for this study is that air gaps can be shimmed accurately without end brackets, certain tests can be conducted at standstill without producing unmanageable locked-rotor currents for the test machines. In practice, synchronous machines running at steady synchronous speeds do not have induced rotor currents.

This study clearly shows that the shaft signals decrease when the rotor of a machine closely situates at the center of its stator bore and tilts slightly to avoid a remaining small eccentricity. Shaft signals increase under greater eccentricities when stator and rotor axes are parallel. Tilted rotors reduce shaft signals.

Inherent positional characteristic exists even when there are no rotor windings. This characteristic produces cyclic shaft-signal components that are related to rotor revolutions. It has a coarse period equal to single revolution. As detailed in the text that the more accurate repeatable period can be calculated, and is greater than a single revolution. At speeds close or equal to synchronous speeds, harmonic components of $(1 \pm 1/p) \cdot f$ caused by inherent positional characteristics are also studied.

The basic frequency of the shaft-signal traces at lower than rated voltage is the supply frequency with certain harmonics. When the machine is operated under saturated conditions, harmonic contents go up significantly. Since shaft only links with asymmetrical portions of flux, tests show that under magnetic saturations the major shaft voltage frequency might not be fundamental.

Shaft voltages corresponding to harmonic components can be generated through inherent rotor positional characteristics.

Parallel of stator windings significantly reduces shaft voltages and shaft flux linkages.

Similar studies on other types of structures are useful. However, the fundamental knowledge obtained in this study helps to understand the shaft voltages of other structures.

Further studies on uses of shaft voltages for monitoring eccentricities, rotor-to-stator rubbings, rotor shorted turns, stator shorted turns of actual electrical machines are being carried out.

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REFERENCES

- [1] G. B. Pollock and J. F. Lyles, "Vertical Hydraulic Generators Experience with Dynamic Air Gap Monitoring," *IEEE Transactions on Energy Conversion*, vol. 7, no. 4, December 1992, pp. 660-667.
- [2] J. R. Cameron, W. T. Thomson, and A. B. Dow, "Vibration and Current Monitoring for Detecting Air Gap Eccentricity in Large Induction Motors," *IEEE Proceedings*, vol. 133, Pt. B, no. 3, May 1986, pp. 155-163.
- [3] A. J. Marques Cardoso, E. S. Saraiva, M. L. Sousa Mateus, and A. L. Ramalho, "On-Line Detection of Air Gap Eccentricity in 3-phase Induction Motors by Park's Vector Approach," *Fifth International Conference on Electrical Machines and Drives, Conference Publication No. 341*, 11-13 September 1991, pp. 61-66.
- [4] P. L. Alger and H. W. Samson, "Shaft Currents in Electric Machines," *Transactions AIEE*, February 1924, pp. 235-245.
- [5] S. P. Verma and R. S. Girgis, "Shaft Potentials and Currents in Large Turbo Generators," Report for the Canadian Electrical Association, Research & Development, Suite 580, One Westmount Square, Montreal, Quebec, H3Z 2P9, May 1981.
- [6] A. Meyer, R. Joho, Z. Posedel, K. Reichert, and C. Ammann, "Shaft Voltages in Turbosets: Recent Development of a New Grounding Design to Improve The Reliability of the Bearings," *International Conference on Large High Voltage Electric Systems*, 1988 Section, 28th August - 3rd September, Paris.
- [7] C. Ammann, K. Reichert, and Z. Posedel, "Shaft Voltages in Turbosets: Operating Experience with RC-Grounding Device and New Possibilities for Monitoring the Condition of Turbogenerators," *ibid.*
- [8] M. J. DeBortoli, S. J. Salon, D. W. Burrow, and C. J. Slavik, "Effects of Rotor Eccentricity and Parallel Windings on Induction Machine Behavior: A Study Using Finite Element Analysis," *Fifth IEEE Biennial Conference on Electromagnetic Field Computation*, Harvey Mudd College, Clearmont, California. August 3-5th, 1992.
- [9] A. E. Fitzgerald, Charles Kingsley, Jr., and Stephen D. Umans, *ELECTRIC MACHINERY*, P. 374, Fourth Edition, McGraw-Hill, New York, NY, 1983.

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