DETECTION AND LOCATION OF INTERTURN SHORT CIRCUITS IN THE STATOR WINDINGS OF OPERATING MOTORS

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Abstract

Motors are critical components for electric utilities and process industries. A motor failure can result in the shutdown of a generating unit or production line, or require that redundant plant be utilized to circumvent the problem. One major cause of failures is breakdown of the turn insulation leading to puncture of the groundwall.

Early detection of interturn shorts during motor operation would eliminate consequential damage to adjacent coils and the stator core reducing repair costs and motor outage time. In addition to the benefits gained from early detection of turn insulation breakdown, significant advantages would accrue by locating the faulted coil within the stator winding. Fault location would not only increase the speed of the repair, but would also permit more optimal scheduling of the repair outage.

This work was successful in practically implementing a theory to predict changes in the axial leakage flux resulting from stator winding interturn shorts and in developing an algorithm to locate the position of the faulted coil. An experimental setup consisting of a 200 hp motor loaded by a generator was used to validate this theory. Suitable transducers were developed and installed on this motor. Measurement using this experimental configuration clearly validated the theoretical model. On the basis of this experimental work, an instrument to continuously monitor for shorted turns is under development.

Key Words: stator, insulation, motor, axial leakage flux

Introduction

Motors are a vital component of the energy conversion process for electric utilities; they provide the motive force for processes such as coolant transport in nuclear plants and coal transport and processing in thermal generating stations. Failure of such motors can result in the shutdown of a generating unit, or require that redundant plant be utilized to circumvent the failure of a particular motor. Whatever the consequences of failure, such events are undesirable since they constitute a decrease in overall system reliability and additional demands on manpower, finance, and time in order to rectify the problem. Similar comments can be equally applied to motors used in process industry applications

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Under an EPRI project, a survey was made of large motors in utility applications [1]. The study found that stator winding breakdown is one of the major causes of motor failure. Other work has indicated that the majority of motor stator winding failures results from the destruction of the turn insulation [2]. Consequently, means to minimize the occurrence, and mitigate the effects, of turn insulation breakdown are desirable.

A typical motor winding has between three and twelve turns per coil. In normal operation, there is usually from 10 to 100 V ac between adjacent turns in a coil. Since the voltage across the turn insulation is relatively low, the insulation is typically only 0.5 mm or so thick. However substantial transient voltages across the turn insulation are possible during switching operations. The turn insulation is often one or two layers of either a dacron-glass tape or a mica-paper tape, bonded by epoxy or polyester resin. In some modern coil designs the strand insulation is upgraded (often using mica-paper) so that dedicated turn insulation is not required.

A large body of work exists on the causes and effects of turn insulation breakdown in motor stator windings [3,4,5,6]. Instrumentation does presently exist to indicate the presence of a shorted turn with the motor removed from service [7]. However, until recently [8,9,10] little work has been performed on the problem of detecting the onset of an interturn short-circuit while the machine is operating.

The purpose of this contribution is to describe a technique based on axial leakage flux sensing, to not only detect the occurrence of a turn fault but also to locate its position in the winding while the motor is operating. Such a technique would have the following benefits.

1. The true cause of a winding failure could be determined. Repairs or rewinds could then address the root cause of a failure rather than a symptom.

2. Although there is no experimental data to indicate the time delay between turn and groundwall insulation failure it is possible that the transition between the two states is not instantaneous. Consequently, shorted turn detection, by indicating the onset of an interturn failure at an early stage, may be able to prevent damage to the adjacent coils and the core thus limiting repair costs.

In addition to the benefits gained from detection of turn insulation breakdown, significant advantages accrue from the ability to locate the faulted coil within the stator winding. Fault location would not only increase the speed of the repair, but would also permit more optimal scheduling of the repair outage. This is because, in some cases, a fast, temporary repair may be effected by cutting the failed coil out of the winding.

Axial Leakage Flux Monitoring

Several workers have proposed the use of phase current monitoring to detect faults such as broken or cracked rotor bars in squirrel cage induction motors [11,12,13]. In these cases the stator is used as a search coil for problems associated with the rotor. The converse of this concept is that the rotor may be used as a search coil for stator faults. Axial leakage flux sensing is a similar technique but detects changes in the line current harmonics indirectly via the axial flux spectrum. This approach is more general than those outlined above and in principle can be applied to a range of common motor faults in both stator and rotor. Penman et al [9] claim that this technique is capable of detecting,

- broken rotor bars
- stator winding interturn short circuits
- wound rotor short circuits
- interturn short circuits on the unenergized windings of doubly wound machines
- loss of phase
- negative phase sequence in supply lines
- eccentric running

For the ideal machine the axial leakage flux is zero. This is because, under fault-free conditions, the rotor and stator currents should be perfectly balanced. However, in practice asymmetries exist in both circuits due to slight imperfections in winding geometry as well as non-uniformities present in the materials of construction. The net effect of these deviations from the ideal machine is to produce a small, but measurable, axial leakage flux.

The premise underlying the use of axial leakage flux as a condition monitor is that faults represent large asymmetries in the machine windings. Hence the effect of a fault will be to enhance the phenomenon of the axial leakage field. From a relatively simple analysis, the harmonics of the axial leakage flux can be derived for any given winding configuration. In addition the harmonic components of interest generated by a particular fault can also be mathematically predicted.

In practice the detection of axial leakage flux is relatively straightforward. All that is required is a search coil placed concentric with the drive shaft of the motor, or a series of coils axisymmetric to the shaft. Typically there is sufficient axial leakage flux so that it is possible to mount the coil, or coils, external to the machine case. Erlicki et al [14] built a protection device based on monitoring the $(2-s)f_1$ component of the leakage flux, where s is the slip. In this way they were able to detect the presence of asymmetry in the supply to the motor.

Harmonic Analysis of the Axial Leakage Flux

The occurrence of a fault on the motor results in a change in the air gap space harmonic distribution. These space harmonics cannot be detected directly by a search coil. However, the search coil can detect the time harmonics of the axial flux. Thus it is necessary to derive the relationship between the space and time harmonics in order to correctly interpret the frequency spectrum obtained from the search coil(s). A further complication which can occur, is the situation in which the motor is fed from an inverter. The inverter is a rich source of harmonics which are injected into the supply lines to the machine, adding further complexity to the analysis. For the purpose of this work only the supply fundamental and the third harmonic component due to saturation are considered.

The space harmonic distribution of mmf due to a balanced, full pitched, three phase winding fed from a balanced supply frequency, ω, is given by [15],

$$\begin{aligned} m = 0.955N_1[&k_{w1}\cos(\omega t-p\theta)+0.2k_{w5}\cos(\omega t+5p\theta) \\ &-0.14k_{w7}\cos(\omega t-7p\theta) \\ &+0.09k_{w11}\cos(\omega t+11p\theta)-...] \end{aligned} \quad (1)$$

where k_{wn} is the n^{th} winding factor
p is the number of pole pairs
θ is the angular displacement from the stator datum

This represents a rotating set of harmonics of order $6n\pm1$ which can be simplified to the corresponding air gap fluxes,

$$\begin{aligned} B_s = &B_1\cos(\omega t-p\theta)+B_5\cos(\omega t+5p\theta)B_7\cos(\omega t7p\theta) \\ &+B_{11}\cos(\omega t+11p\theta)... \end{aligned} \quad (2)$$

where B_n are the spatial harmonic fluxes.

This expression is in the stator frame of reference. Consequently, because the shaft flux of the rotor is of interest, it is necessary to refer equation (2) to the rotor reference frame. Consider the situation in which ß is the angular displacement between the rotor and stator datum positions, and α is defined to be the angular displacement from the rotor datum. Then $\theta = \alpha + \beta$.

If the angular rotor speed is ω_r, then,

$$\theta = \alpha+\omega_r t \quad (3)$$

now using the normal expression for the slip of the motor, i.e. $s = (\omega_s-\omega_r)/\omega_s$, where ω_s, the synchronous speed, $= \omega/p$,

$$\omega_r = \omega(1-s)/p \quad (4)$$

Now, the general term of equation (2) is,

$$B_{ns} = B_n\cos(\omega t\pm np\theta) \quad (5)$$

substituting equations (3) and (4) into (5) leads to,

$$B_{ns} = B_n\cos[(1\pm n(1-s))\omega t\pm np\alpha] \quad (6)$$

Expanding the expression for the first few terms gives,

$$\begin{aligned} B_s = &B_1\cos(s\omega t-p\alpha)+B_5\cos[(6-5s)\omega t+5p\alpha] \\ &-B_7\cos[(7s-6)\omega t-7p\alpha]+B_{11}\cos[(12-11s)+11p\alpha]-... \end{aligned} \quad (7)$$

Equation (7) gives the frequency components of the currents that are induced in the rotor due to the air gap space harmonics of a balanced winding and supply. In addition to these harmonics, the fundamental of the supply frequency will also appear in the axial flux spectrum. The presence of additional, higher order harmonics can be accounted for by using $n\omega$ rather than ω.

The effect of the interturn fault is to remove a turn from the stator winding. This will have a small, but finite, effect on the main air gap flux distribution. In addition, an emf will be induced in the shorted turn which will result in a current flow limited only by the self impedance of the fault. This impedance essentially determines the transition time between turn and groundwall insulation failure.

The fault current due to the shorted turn is the source of an additional mmf pulse, which also has a space harmonic distribution which is superposed on the main field distribution. From previous considerations, it follows that this will lead to a change in the time harmonics observed in the leakage field. These effects form the basis of the fault identification technique. The changes expected can also be predicted mathematically.

Simple consideration of the mmf distribution due to an interturn short circuit leads to the characteristic illustrated in Figure 1. This is the case for a four pole machine. The analysis to be outlined is for the general case of the 2p pole machine.

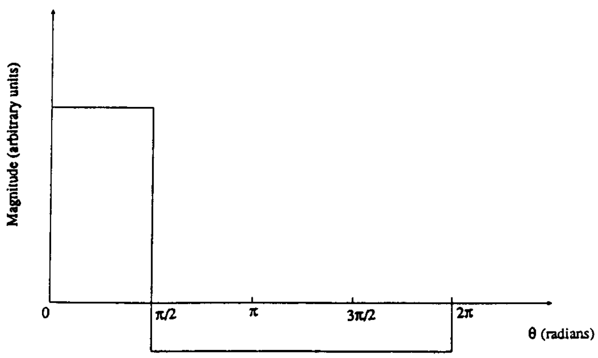


Figure 1. MMF due to a shorted turn

Fourier analysis of the mmf waveform, illustrated in Figure 1, shows that it contains all harmonics except the fourths, i.e.,

$$B_s = 0.5\Sigma B_n\cos(\omega t \pm n\theta),\ n \neq 4m,\ \text{all } m \tag{8}$$

For the general case, the corresponding waveform would have a mark-space ratio of 1:(2p-1) causing every $2p^{th}$ harmonic to be absent. Hence the time harmonics produced by the rotor are given by,

$$B_s = 0.5\Sigma B_n\cos[(1 \pm n(1-s)/p)\omega t \pm n\alpha],\ n \neq 2pm,\ \text{all } m \tag{9}$$

Adding in supply time harmonics of higher order k, leads to the completely general expression,

$$B_s = 0.5\Sigma\Sigma B_n\cos[(k \pm n(1-s)/p)\omega t \pm n\alpha],\ n \neq 2pm,\ \text{all } m \tag{10}$$

Although this is a large series, only the lower order harmonics are significant. The key element of this expression is,

$$[k \pm n(1-s)/p]f_1 \tag{11}$$

for k = 1,3 and n = 1,2,3,.....,(2p-1)

The $n\alpha$ term in the argument of (10) causes the components defined above to beat at the slip frequency of the rotor current.

The Location of Turn Faults

The occurrence of an interturn short circuit results in a disruption of magnetic field symmetry in the end winding region of the motor as well as increasing the magnitudes of certain harmonic components. This is because there is a severe imbalance between the current flowing in the shorted turn and the corresponding diametrically opposite turn in the winding. Hence a possible method to locate the position of the shorted turn is based upon localized measurement of the magnetic field in the end region.

In practice the location technique requires the use of a minimum of four search coils located axisymmetrically to the drive shaft in the end plane of the machine. In order to perform the location function, using the search coils, it is necessary to derive an expression for the field at any point on the circumference of an imaginary circle passing through the centres of the coils. This field is due to the current flowing in the end winding of an arbitrarily positioned turn of the stator winding, acting alone.

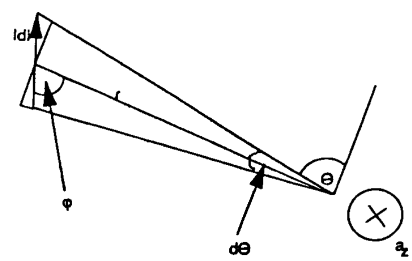


Figure 2. Geometry required to calculate magnetic field acting on search call

Using the Biot-Savart law, and referring to Figure 2,

$$d_B = (\mu_o I \underline{dl} \times \underline{a_z})/4\pi r^2 \tag{12}$$

where $\underline{B}$ is the magnetic field strength vector
μ_0 is the permeability of free space
$\underline{a_z}$ is the unit vector in the z direction

From Figure 2, and rewriting equation (2)

$$dB = (\mu_o I dl \sin\varphi)/4\pi r^2 \tag{13}$$

but $dl\sin\varphi = r d\theta$, thus

$$dB = (\mu_o I d\theta)/4\pi r \tag{14}$$

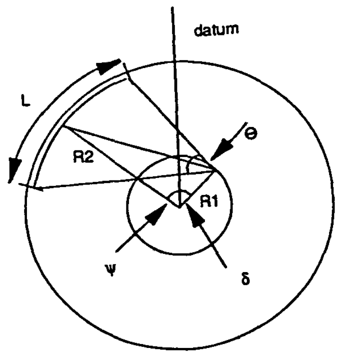


Figure 3. Geometry of the general case to calulate field due to a shorted turn

Figure 3 illustrates the general case in which the shorted turn is displaced an angular amount, Ψ, from an arbitrary datum position. In this case R_2 is the mean radius of the end winding, and R_1 is the radius of the circle on which the field is to be calculated. The circles are assumed to be coplanar and concentric. The length of arc of the coil is L and the field measurement point is displaced an angle δ from the datum. Using the cosine rule,

$$r^2 = R_1{}^2+R_2{}^2-2R_1R_2\cos(\Psi+\delta) \tag{15}$$

If R_2 is very much greater than R_1, then $L \approx r\theta$, thus

$$\theta = L/[R_1{}^2+R_2{}^2-2R_1R_2\cos(\Psi+\delta)]^{0.5} \tag{16}$$

From equations (14) and (16), the value of B at the field point is given by,

$$B = \mu_0 IL/[4\pi(R_1{}^2+R_2{}^2-2R_1R_2\cos(\psi+\delta))] \tag{17}$$

By fixing the position of a number of coils with respect to the datum, and arbitrarily assigning a reference coil at $\delta = 0$, the value of B at each coil can be found as a function of ψ. From the measured values of B, ψ can be found and consequently the position of the faulted turn.

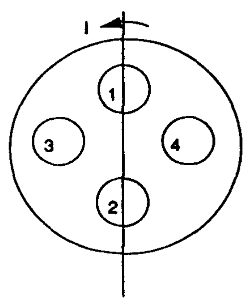


Figure 4. Minimum coil geometry for reliable turn fault location

Consider the situation in which two coils are spaced 180° apart. Each coil will have an induced emf, proportional to the flux linking it. With reference to Figure 4, and taking the coil at position 1 to be the datum, from equation (17),

$$B_1 = k/(a-b\cos\psi) \tag{18}$$

and

$$B_2 = k/(a-b\cos(\psi+180°)) \tag{19}$$

$$\text{thus } B_2 = k/(a+b\cos\psi) \tag{20}$$

where $k = \mu_0 IL/4\pi$
$a = (R_1{}^2+R_2{}^2)$
$b = 2R_1R_2$

From equations (18) and (20), and some rearrangement of the terms,

$$\cos\psi = [a(B_1-B_2)]/[b(B_1+B_2)] \tag{21}$$

This expression locates the fault to within $\pm\psi$ because,

$$\pm\psi = \cos^{-1}[0.5(R_1/R_2+R_2/R_1)\{(B_1-B_2)/B_1+B_2)\}] \tag{22}$$

In practice the measured values of the emf induced in the coils can be used because the B values are ratioed in equation (22).

Consequently the values used when attempting fault location should be the modulus of the difference between the "healthy" and "faulted" conditions. In order to uniquely locate the fault, a second set of coils, 3 and 4, is required. For convenience they are displaced at right angles to the axis of symmetry of coils 1 and 2. However, the angular displacement of the coils is not critical. Repeating the location procedure in the same fashion as above with the second set of coils, will yield $\pm\psi_{p2}$, which differentiates it from $\pm\psi_{p1}$, found from coils 1 and 2. If the higher magnitude coil signal is chosen as the point from which to measure, then ψ will always fall within the range of 0° to 90°. In addition, only one quadrant will contain an angular position identified using both sets of coils. This is the approximate location of the fault.

Test Motor Setup

A surplus motor-generator set with form-wound coils which could be loaded and have controlled interturn short circuits injected was procured. The motor is rated at 550 V, 190 A, 720 rpm and has a wound rotor with sliprings feeding a resistor bank for speed control. The motor was delta connected, with two parallel paths per phase, and a total of 108 coils with each coil having 6 turns. The full-load, line current of 190 A results in a normal turn current of about 55 A. The motor is directly coupled to a dc generator which would normally be used to feed the field of a hydraulic generator. Control of the generator output is via a shunt winding and a variable resistor. Loading of the dc generator was accomplished by two large water-cooled resistors.

At the nose of two stator coils (one on each side of the machine), the insulation was bared and the top two copper turns exposed. A set of leads was attached across one turn of each of the coils. These leads fed a water cooled variable resistor (similar to the resistors used to load the generator). Varying the resistance value allowed the short current to be varied while still protecting the motor from severe overheating. By measuring the link current through the resistor and comparing it to the motor phase current, it is possible to accurately determine the short current flowing in the motor turn. Because the machine has two parallel paths per phase the short current can be calculated as:

$$I_s = I_l - I_p/2$$

where:

I_s = short current
I_l = link current measured through the shorting resistor
I_p = phase current of the motor

Note that one motor phase consists of two parallel paths of 18 coils with 6 turns each for a total of 108 turns per phase. Thus it is virtually impossible to distinguish any change in the stator phase current when a short is introduced in a single turn. A 200-A circuit breaker was installed to allow the turn short to be switched on and off at will. A series resistance of about 0.1 Ω was chosen to limit the link current to approximately 100 A, thus protecting the motor from complete failure when the short is introduced.

Two types of search coil were used in this work. A large coil was installed concentrically around the shaft of the motor at one end of the machine. The coil was constructed from about 300 turns of #18 wire wrapped around a plexiglass former bolted around the motor shaft.

In order to locate the fault position, four smaller coils were mounted symmetrically in the four quadrants of the motor at a radius of about half the distance from the shaft to the stator endwinding. These search coils consisted of approximately 100 turns of #18 wire on a 12.5 cm diameter plastic former.

Detection of Shorted Turns

Using equation (11), it is possible to predict the expected harmonics for our test motor, Table 1. The significant harmonics for detection of shorted turns are the those with the lowest n*k product and for our particular motor are at approximately 48 Hz, 72 Hz, and 84 Hz (these frequencies vary slightly depending on the motor loading or slip). As the motor loading changes, the magnitude of the various harmonics can also be expected to change.

n	K=1		K=3	
	+	-	+	-
1	71.88	48.12	191.88	168.12
2	83.76	36.24	203.76	156.24
3	95.64	24.36	215.64	144.36
4	119.4	12.48	227.52	132.48

Significant harmonics with motor slip of 1%

Table 1. Expected Harmonics with a 1% Motor Slip

An HP 3582 spectrum analyzer was used to monitor the axial leakage flux components from the centre coil. This spectrum analyzer can resolve frequencies down to 250 mHz over our frequency range of interest (0 - 200 Hz). In addition to the HP spectrum analyzer, a Fluke 87 multi-meter was used to make measurements of the rms emf values on each of the four auxiliary coils.

With the motor unloaded, all of the expected harmonics were present in the axial leakage flux measurement from the center coil, Figure 5. However each of these harmonics beats with the slip frequency of the motor. Thus the peak hold feature which retriggers the device to sample the waveform a number of times and displays the largest reading obtained at each frequency during the sample period was used.

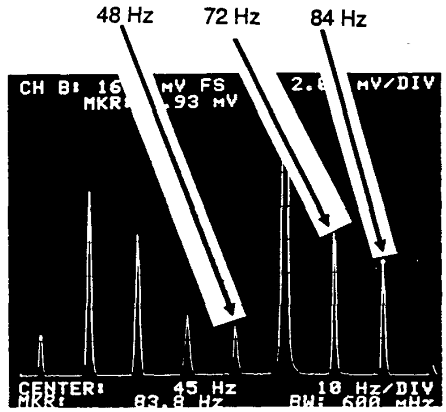
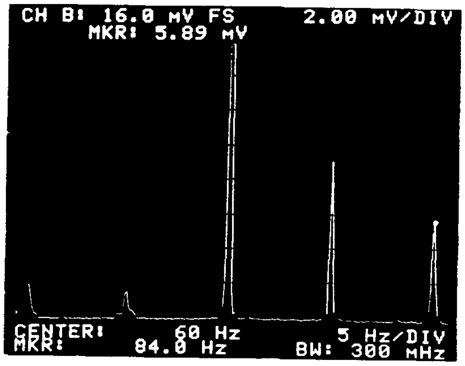


Figure 5. Axial Leakage Flux Measured by the Center-CT

As the motor loading was increased, the relative magnitude and center frequency of the various harmonics shifted slightly as predicted. Measurements of the axial flux components with the motor unloaded using the centre coil, with and without a shorted turn, are shown in Figures 6a and 6b respectively. The short circuit current in this case was limited to 50 A. The magnitude of the specific harmonics of interest are tabulated in Table 2. As shown by these results, a significant change in the specific harmonics of interest was detected.

The motor was then loaded to 48 kW and the measurements repeated. The resulting axial leakage flux measurements from the centre coil are tabulated in Table 3. Although the magnitudes of the specific harmonics of interest increased with motor load, the relative change for the unshorted vs shorted condition remained significant.

These measurements demonstrate that it is both practical and feasible to detect a shorted turn in a stator winding using relatively simple axial flux leakage measurements. The coil used to make these measurements is inexpensive to build and can be easily retrofitted to most motors. The electronic circuitry necessary to measure the magnitude of the specific harmonics in the axial flux signal is relatively simple. However it should be recognized that this technique cannot be applied on a single measurement basis but requires a fingerprint of the flux while no turn short is present.



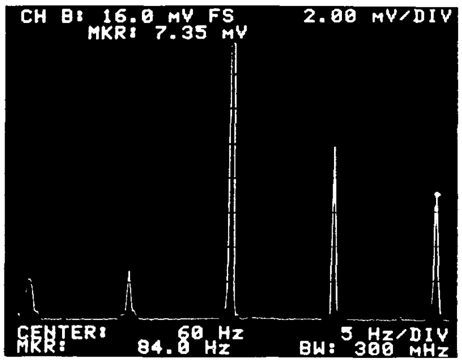


Figure 6. Axial Flux With (b) and Without (a) a Shorted Turn. The frequency components (left to right) are 36, 48, 60, 72 and 84 Hz.

Frequency (Hz)	No Short Is = 0	Short Is = 50 A	Difference
48	1.65	2.7	1.05
72	9.2	10	0.8
84	5.9	7.35	1.45

All readings in mV

Table 2. Axial Leakage Flux Magnitudes at Significant Frequencies for the Unshorted and Shorted Conditions Center-CT Inboard of Motor

Frequency (Hz)	No Short Is = 0	Short Is = 50 A	Difference
48	48	55	7
72	141	170	29
84	71	84	13

All readings in mV

Table 3. Axial Leakage Flux Magnitudes at Significant Frequencies for the Unshorted and Shorted Conditions With the Motor Loaded

Location of Shorted Turns

Utilizing the four auxiliary coils mounted in the endwinding of the machine, a measurement of the rms flux magnitude at various locations in the endwinding was made. As described above, the change in readings from these four auxiliary coils for the unshorted and shorted cases can be used to triangulate the area of unbalanced flux and hence locate the shorted turn.

The initial measurements of the rms flux magnitude on the four auxiliary coils were made using the Fluke 87 for the motor with and without a turn fault. Measurements made with these coils with the motor both loaded and unloaded are shown in Table 4. Substitution of these values into equation (22) with $R_1 = 30$ cm and $R_2 = 45$ cm locates the fault within a sector of arc 18^o from coil 0, where the defeat is located, for the unloaded condition. When the motor is loaded the uncertainty decreases to 10^o.

Coil Location 0|1 / 2|3		No Load Motor: Current = 74 A, Speed = 718 rpm Generator: Output Current = 0, Output Voltage = 0			Loaded Motor: Current = 101 A, Speed = 714 rpm Generator: Output Current = 300 A, Output Voltage =155 V		
		No Short	Short IL = 125 A IS = 88 A	Δ	No Short	Short IL = 125 A IS = 75 A	Δ
Coil	Position	mv	mv		mv	mv	
0	TE	5.8	30.1	24.3	8.8	37.1	28.3
1	TW	19.4	18.4	1	27.9	27.1	0.8
2	BE	18	19.4	1.4	25.2	26.3	1.1
3	BW	11	11.8	0.8	16	16.3	0.3

Table 4. Axial Leakage Flux Measurements using 4 Auxiliary-CT's Under Unshorted and Shorted Conditions

In order to determine the feasibility of constructing a continuous on-line monitor, a simple shorted turn detector was built and tested. The device was relatively crude, using programmable analog filters under computer control to obtain magnitude information at each of the predetermined frequencies. A more elegant approach would be to use a fast Fourier transform (FFT). However, despite the limitations of this approach, performance in detecting and locating the defect comparable with the testing described above was achieved. A more sophisticated device based on an embedded microcontroller is under development.

Conclusions and Further Work

The theoretical background for detecting shorted turns in multiturn motor stator coils has been elucidated and practically demonstrated on a 600 V, 200 hp motor. Furthermore, an algorithm has been developed which enables location of the defective coil within the stator winding. The location algorithm was also successfully tested on the experimental motor used in this work. Neither the detection nor location techniques require the motor to be loaded.

Although a crude instrument was developed to assess the feasibility of constructing an inexpensive automatic shorted turn detector and locator, further development is ongoing to produce an instrument capable of operation in the plant environment. Work is also continuing on optimization of the design, number and location of the search coils. Further research is also planned on determining the key parameters governing the transition time between turn insulation breakdown and groundwall failure.

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