A Winding Tester
– a New Means to Detect Wear in the Insulation in Electrical Machines.

1 - Executive summary.

Until this moment in history it has not been possible to monitor the development of wear in the insulation in electrical machines i.e. motors, generators and transformers. Not until deteriorated insulation has caused partial discharges, and thereby indicated an imminent fatal winding failure, has the wear hitherto been detectable. This paper presents a new means to monitor the development of the deterioration in the wire insulation in electrical machines and thus provide peace of mind for their owners.

The concept is based on monitoring the shift in the resonance frequencies of the resonance circuits constituted by the inherent inductance of the winding turn(s) and the (increasing) capacitance caused by the declining thickness of the layer of the lacquer insulation in the areas where the insulation gets worn.
The shift in resonance frequencies can be detected by measuring the machines winding impedances Z(s) as a function of the frequency.

The concept leads to a four-fold commercial application.

a. Selling and buying information (/experience) to- and from the winding tester customers.
b. Selling hardware in form of portable hand-held winding testers.
c. Selling hardware and/or services in form of stationary monitoring equipment (for e.g., wind farms, power plants, high power transformers etc.).
d. Using the gained knowledge in production of electrical machines.

2 - Number of electric motors and their power consumption.

- Approximately 700 million motors are in operation worldwide.
- Worldwide approx. 50 million motors are annually put into operation.
- In USA electric motors annually consumed 679 billion kWh (1994 figure)/(One USA billion = 10^9).

(Source: http://what-when-how.com/electric-motors/the-impact-of-motor-efficiency-electric-motor/)

3 - The concept.

Most electricians would diagnose an electrical machine by comparing the currents in its three phases or by using a comparative measurement of differences in the resistances of the three windings. But not until a fatal breakthrough in the wire insulation has occurred will one be able to detect any significant change in the resistances of the three windings nor any significant change in the phase currents. Thus, these methods cannot be used to predict the remaining lifetime, until just before the machine is about to perish.

The following pages present a new concept for detecting wear in the winding insulation in electrical machines. This method also allows to establish, which of the phase windings is about to perish.

Wear in electrical machines leads to reduced thickness of the lacquer insulation of the wires, which in turn, causes a change in the capacitance between adjacent (wire-) turns in the machine.

The detection of the changes in the capacitance can be done either in:

a. The frequency domain i.e., the impedance Z(s), and/or
b. The time domain i.e., through the change in the propagation delay through of the windings.

In the section “Comparing measurement in the time domain versus measurements in the frequency domain.” I shall present my reasons for advocating the detection in the frequency domain.

As said, when the insulation between adjacent turns gets worn it means that the wire insulation gets thinner. The capacitance between adjacent turns can be compared to a disk capacitor, where the core of the wire constitutes the capacitor disks and the wire insulation provides the dielectric.

Any changes in shape, distance and/or dielectric (e.g., due to disintegrating lacquer) will cause a change of the capacitance between the cores of the two adjacent turns. Together with the inductance L of the turn (or turns) between the areas, which forms the capacitance C, the L and the C constitutes a resonance circuit with a resonance frequency: $f_{Res.} = (2\pi)^{-1} * (LC)^{-½}$. This resonance frequency will be only one out of numerous resonance frequencies - each of which will be defined by its inductance and its capacitance.

Throughout the operational life of the machine and up to the moment of failure, the physical configuration, hence the number of turns and thus the inductance between any such areas will remain unaffected by the wear and tear of the machine. Hence, as long as the cores of the two adjacent turns in the winding have not yet shorted together, the inductance L between the two areas remains unaffected by the wear. The capacitance, however, will increase by the wear of the insulation. Hence, as the insulation gets worn, the resonance frequency - associated with capacitance C and the inductance L between the two worn areas - will drop.

Note that already during the production of the machine, as the wire tension is applied by the winding machine, and the wire is drawn down to rest on top of the underlying layers, the deterioration of the wire insulation will be started.

To summarize: The resonance frequency of the resonant circuit(s), which encompass(es) the wear will be shifted downward in frequency - causing the impedance Z(s) as a function of the frequency f (where $s = j\omega$ and $\omega = 2\pi f$ is the angular frequency) to change.

4 - The toll of undetected windings faults.

There are good reasons why faulty windings in electrical machines should be found as early as possible:

1. To spot faulty electrical machines before they break down unexpectedly and stop a production.
2. In order to stop excessive power consumption caused by faulty windings.

Today faulty windings are seldom found until the fault develops into a level where either the circuit breaker or the fault current relay trips. (The rare exception could be when thermo-graphics is applied.) Once the circuit breaker or the ground fault current relay trips, it generally comes as a surprise. Yet, during the time leading up to this moment, the machine will often have used significant excessive kWh.

5 - The use of transformers by the utilities.

Apart from the power in non-grid connected systems, virtually all electrical-power in this world passes through the transformers of the utilities. In Denmark the utilities do nothing to monitor the 10/0.4kV transformers to prevent breakdowns. The 400/150 kV, the 150/60 kV and the 60/10 kV transformers are monitored in the form of periodic (every couple of months) gas-analyses of the cooling oil.
(Source: Lars Andreasen; NRGI-utility and John Pedersen N1 Distribution.)

Short-circuits in grid transformers cause power cuts and black outs. Hence, some utilities change their transformers prematurely – others react too late!

6 - The reasons for wear in windings and the attempts taken by the manufactures to overcome them.

The reasons for wear in windings are numerous:

1. Each change of the current through a winding causes a change in the magnetic flux and, thus, in the forces acting between the turns. And each change of force causes a (tiny) movement of that wire/turn – which in turn causes a wear in the insulation of that same turn.

2. Each change of torque/load on a motor/generator shaft will cause a similar change in the magnetic field, which likewise will cause movements of wires, and hence wear, of the wire insulation.

3. Changes of temperature will not be uniform throughout the winding. From figure 3 (below) it is seen that turns in different layers will have the same expansion coefficient - but different thermal resistances to the ambient, and hence, different temperatures. The different expansions cause internal movements (i.e., rubbing between the winding layers), which will add to the wear of the insulation. Hence, intermittent operation causes increased wear and shorter lifetime.

The consequences of sloppy windings are well known to the manufacturers of electrical machines. Many motor- and generator manufactures employ particularly skilled people who know the art of binding the windings at the ends of the stator. The windings at the ends of the stator are bound in order to solidify the turns relative to one another – and thus to curtail movements of the turns.

Transformer manufacturers likewise struggle to secure and fix the turns relative to one another, to the bobbin and/or to the core by impregnating the windings with lacquer - or casting the entire transformer in a moulding. Windings in transformers in the kV and kW/MW class can, however, generally not be moulded, as they require oil to cool the windings.

Along with the physical wear, the insulation lacquer also exhibits a natural decomposition (over time).
The Svante Arrhenius equation states that the rate constant k, for the temperature dependence of reaction is: $k = A\,e^{-Ea/(RT)}$ - where:
T is absolute temperature in Kelvin,
Ea is the activation energy - and
R is the Universal gas constant.

In practice the rate of decomposition will increase by a factor of approximately 2.2 – 2.3 times by every 10 degrees increase in the temperature. Hence, manufacturers strive to keep the windings cool, by filling up all possible voids in the winding.

7 - The capacitance between the turns, linked with the thermal resistance from the turns to ambient.

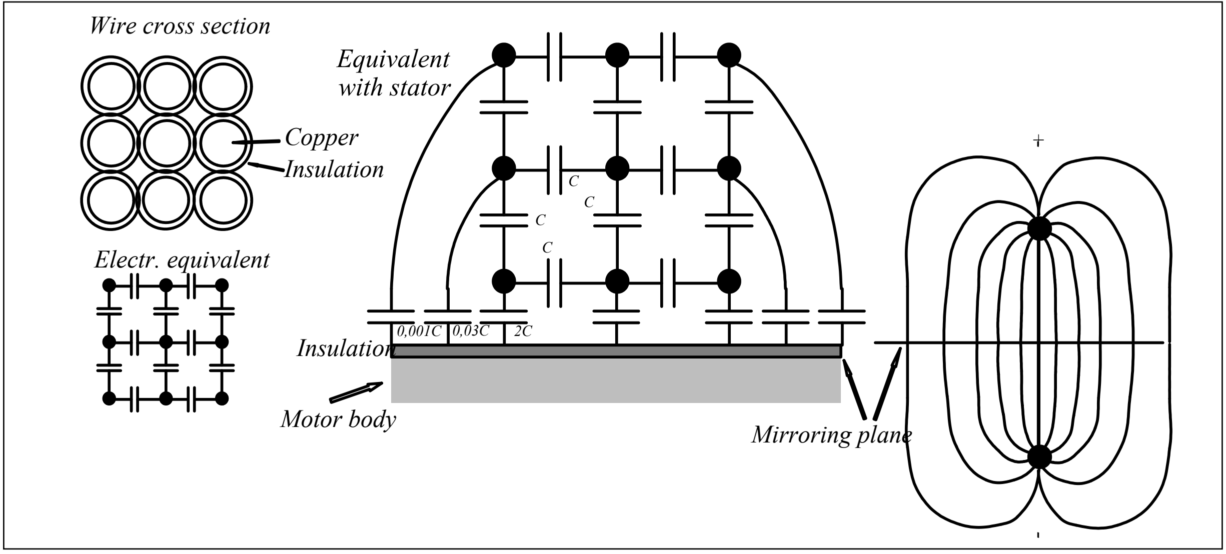


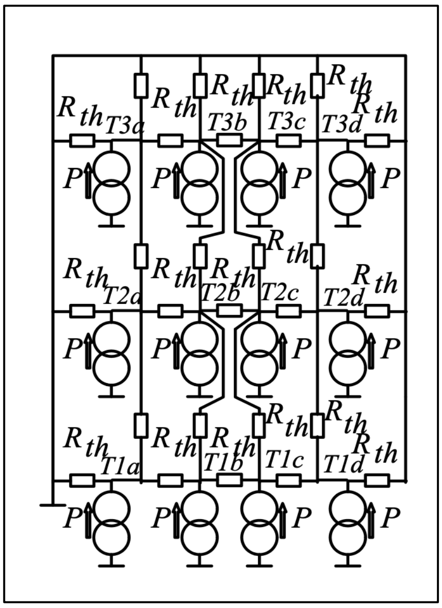
Figure 2. Showing a cross section of windings insulated from a core and their electrical equivalent.

Upper left in figure 2 are shown the windings with their insulation coating of e.g., lacquer.
The windings are generally wound either on a bobbin or self-supported on top of a separate layer of insulation (protecting the lacquer insulation from being damaged by sharp edges of the core/motor body). (For the sake of the simplicity the capacitances between the two upper middle turns and motor body are not shown on the drawing.)

Figure 3 (below) shows a two-dimensional approximated thermal equivalent of a winding with 3 layers – each layer consisting of 4 turns - in an electrical machine.

T_{np} is the temperature of the n’th layer and p’th turn.
R_{th} is the thermal resistance between adjacent turns.
P is the power dissipated per turn.
“Ground” represents the ambient temperature.

Figure 3.



Comparing figure 3 to the wire cross-section and the schematic of the electrical equivalent in figure 2, one realizes:

a. The similarity between the mechanical, the electrical and the thermal structures.
b. That the highest densities of electrical field lines occur where the turns rest on top of each other. As the electrical field strength in a capacitor is inversely proportional to the distance between the plates, a change/wear in the insulation will be reflected in the capacitance.
c. That the heat flow from the winding to the ambient will predominantly pass through the same points of contact between adjacent turns – which also determine the capacitances.

8 - The inductance and the resonance frequencies between adjacent turns.

For windings made on common windings machines, adjacent turns (i.e., adjacent knots in the electrical equivalent in figure 4) in the horizontal plane will have one turn between them. Yet, for a winding (with Q turns per layer) adjacent turns in the vertical plane can have any number (q) of turns between them (where q can be any integer between 1 and 2Q), depending on where (horizontally) in the layer the deteriorated insulation is situated.

The inductance L is proportional to the square of the number of turns. Hence, the inductance L is these vertically adjacent turns is approximately proportional to the square of q, where q is the number of turns between the two adjacent turns. The inductance L is proportional to K q^2 - where K is a constant, which depends on the magnetic properties and the physical shape of the core – and $f_{Res.} = (2\pi)^{-1} * (LC)^{-½}$. Hence, the vertically adjacent turns - which are the most susceptible to damage - are also the ones which will have the lowest resonance frequencies.

Adding to this, comes, that the bottom layers, which will generally be clamped in place by the pressure from the top layers – thus less likely to move relative to one another than the top layers – and consequently less susceptible to wear in the lacquer.

Thus, the capacitances between turns - which have the highest probability to short circuit - will generally also have a significant higher inductance between them, hence lower resonance frequencies. Linking this with the paragraph above points us to focus on the low frequency range.

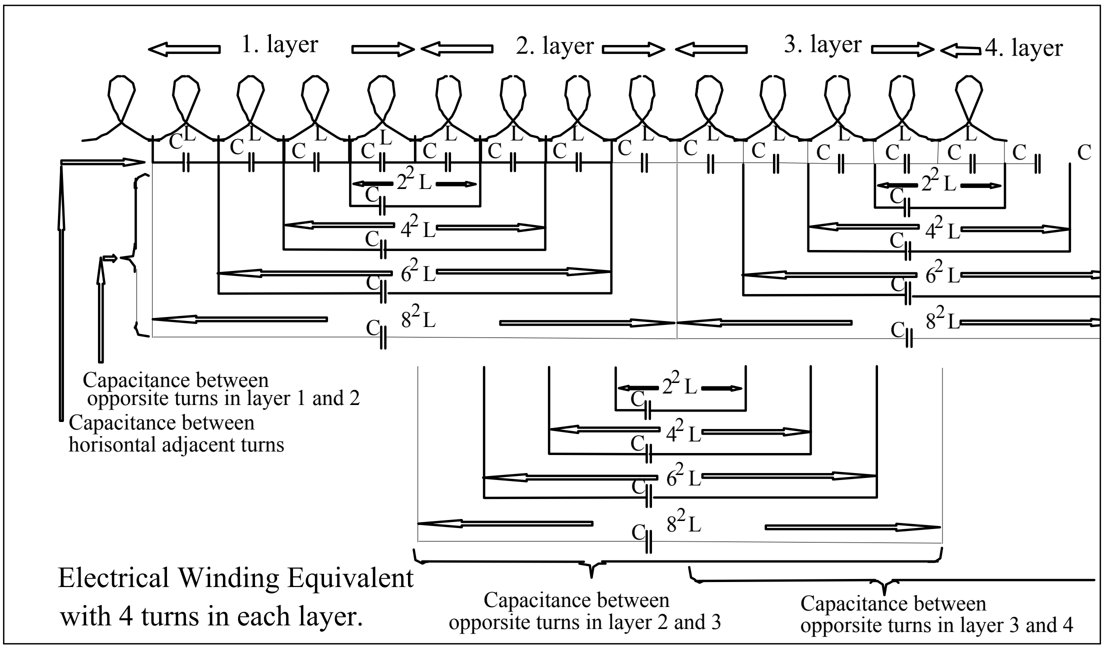


Figure 4. An equivalent schematic showing the capacitance of horizontal and vertical adjacent turns.

This complies with my personal observations, that the most vulnerable spots in windings are the areas where the turns rest on top of each other. Transformers, on which I have carried out post–mortem examinations have generally show faults between layers resting on top of each other – rather than faults between turns within the same layer. It also supports the conjecture, that the deformation of the wires and their insulation - caused by the wire tension and the torque applied during the winding process – plays a significant role in the faults.

9 - The impedance of rotating machines at harmonics >2.

For a healthy electrical machine, the high number of resonance circuits in series and parallel will lead to an impedance Z(s) more or less as the one shown at figure 5 (below). For frequencies $f = h^* f_o$ and $h = 6n+1$ (where f_o is the mains frequency and n = 1, 2, 3…) the harmonics will produce a flux rotation of the ***same*** direction as the direction of the rotating field, which is created by the fundamental frequency f_o.

Opposite to harmonics with $h = 6n+1$, all harmonics with $h = 6n-1$ (where n = 1, 2, 3…) will produce a flux rotation of the ***opposite*** direction of f_o. As the rotor at any given time can only rotate in one direction and at one angular speed (corresponding to f_o, minus the slip), the torques created by all other frequencies than fundamental (f_o), will be locked by the rotor/armature (this corresponds to a transformer with a shorted secondary winding). Hence, by these harmonic frequencies the impedance of the windings Z(s) will appear as dips in the impedance Z(s) of the winding (as shown on figure 5 following).

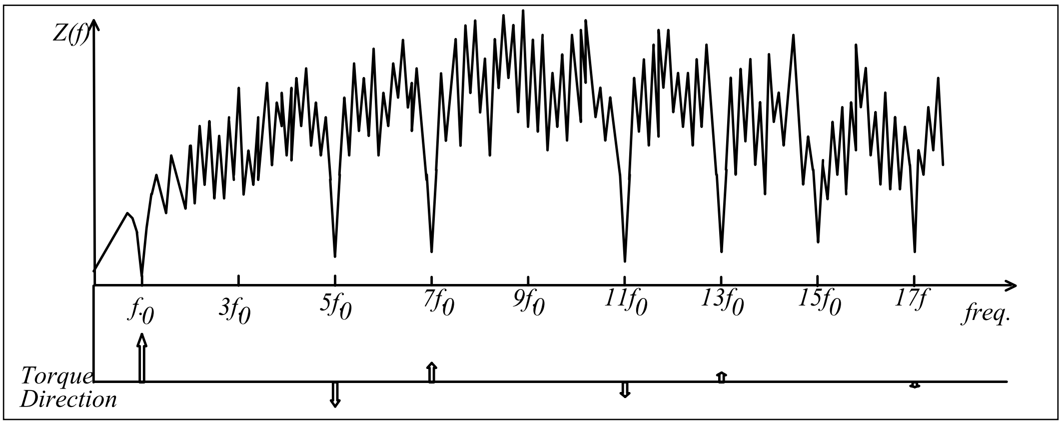


Figure 5. A fictional example of the impedance Z(s) of a rotating machine as function of frequency.

Thus, when a rotating electrical machine is driven by non-sinusoidal currents, shifts in resonance frequencies might be masked at the above stated frequencies (i.e. 5 f_0, 7 f_0, 11 f_0, 13 f_0, …etc).

Thus, during the measurement of a motor or generator (for winding wear) it is preferable that the currents to the motor / generator should be sinusoidal; or that the machine should be switched off.

10 - Detecting local minima in the impedance is more reliable than detecting local maxima.

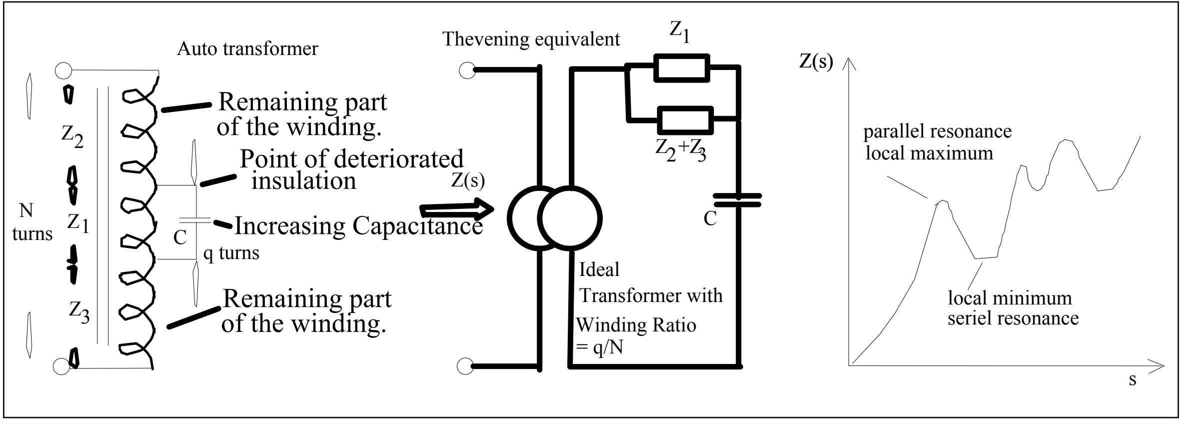


Figure 6. Left: A deteriorated insulation across a fraction of a winding; Middle: The corresponding Thévenin equivalent - and Right: The impedance as function of s = jω.

From figure 6 left it is seen how the deteriorated insulation and the associated increased capacitance correspond to an autotransformer loaded with a capacitance. As the mutual inductance M between any two windings can never achieve 1.0000, there will always exist a minimum leakage inductance between the winding sections designated Z_1, Z_2 and Z_3. At the low end of the frequency range Z_1, Z_2 and Z_3 will be dominated by inductances.

The middle of figure 6 shows the Thévenin equivalent of the winding. Z_1, Z_2 and Z_3 are all assumed to be purely inductive, in which case the Zs together with the increasing capacitance form a series resonance circuit. Z_1 corresponds to the inductance between the two worn insulation areas. The Z_2 and Z_3 represent the sum of the magnetizing reactances and the mutual coupling to Z_1, for each of the winding sections (Z_2 and Z_3) on both sides of Z_1.

To the right is shown the impedance as a function of s (the angular frequency) as seen from the winding terminals. The (numerous) maxima and minima at higher (and/or) lower frequencies originate from the distributed capacitances between the turns in the rest of the winding.

Assuming that M = 0 and Z_1, Z_2 and Z_3 are purely reactive where $Z_1 = L_1$ and $Z_2 + Z_3 = L_2$.

Z(s) becomes:

$$Z(s) = sL_2 + sL_1 \mathrm{II} (sC)^{-1} = \frac{sL_1 + s^2C(L_1 * L_2) + sL_2}{1 + s^2CL_1}$$

where sL_1 II $(sC)^{-1}$ means the impedance of L_1 and C connected in parallel.

$$\Rightarrow Z(s) = s(L_1 + L_2) * \frac{1 + s^2C(L_1 \mathrm{II} L_2)}{1 + s^2CL_1}$$

where (L_1 II L_2) means the parallel connection of L_1 and L_2.

As can be seen from the expression of Z(s) it has one pole at $s = (C\,L_1)^{½}$

and two zeros at $s = 0$ and $s = (C\,(L_1 \text{ II } L_2))^{½}$.

Anyone who has tried to measure a magnetizing reactance in windings by connecting a large capacitor across the terminals and looking for the peak in the impedance as a function of the frequency, will probably have noticed several maxima and minima in Z(s). Sometimes this makes it difficult to define the main parallel resonance frequency associated with the magnetizing reactance.

At times a winding can be wound so that other resonance circuits within the winding will mask (or offset) the detection of the parallel resonance frequency.

Another issue of measuring the parallel resonances is that the high impedance level at the resonance frequency of a parallel resonance circuit makes the measuring more susceptible to noise and other disturbing factors. Hence, rather than detecting the maxima of the impedance Z(s) it is more reliable to detect the minima.

Comparing figure 6 to the analytic expression of Z(s) for purely reactive values of Z_1, Z_2 and Z_3, one realizes that for every peak (maximum) in impedance Z(s), a corresponding dip (minimum) will exist.
And if a parallel resonance frequency will shift - so will the associated serial resonance frequency based on the same capacitance - also shift its resonance frequency.

By these arguments I have convinced myself - and hopefully you as well - that the frequency of the dips in the plotting of Z(s), will be a function of the sum of the two lacquer thicknesses of the adjacent turns. Hence, once the lacquer thickness of a specific touching point between any two turns has been reduced by wear, the corresponding dip in the Z(s) plot will likewise have been shifted downward in the spectrum.

11 - The number of resonance frequencies to be detected.

The number of resonance frequencies to be detected will be high. To get an idea of the number of capacitances we will look at a low power motor. Low power motors and generators generally have a higher number of turns than their high power cousins. Consider a three-phase 300W 230/400V motor. Each of the 3 windings has N =1000 turns. Assume that each turn is encircled by six adjacent turns. This gives C' = 6 contact points around each turn. Hence, a rough estimate of the number Q of capacitances of interest in the motor is:

$$Q \;=\; 3 \text{ phases} * N * \tfrac{1}{2} * C' \;=\; 3 * 1000 * \tfrac{1}{2} * 6 \;\approx\; 10{,}000 \text{ capacitances.}$$

For high voltage transformers the number is estimated to be in the order of tenfold higher.

The number of permutations of inductances that each of the capacitances can resonate with will be in the order of N!

In other words, the theoretical number of resonance circuits in an electrical machine will be astronomical. Yet, as the magnetic flux will predominantly pass through the magnetic core of the machine, so will the inductance per turn be more or less the same no matter where in the winding the turn is situated.

Likewise, one realizes, that the capacitance per unit area between the healthy turns of the windings will also be more or less the same. Thus, despite the astronomical number of resonance circuits the vast majority of these resonance frequencies will be bundled into groups – each comprising an integer number of turns.

It can also be seen, that each bundle will pose almost identical resonance frequencies, Thus, with all these almost identical resonance circuits connected between the winding terminals, their total impact on Z(s) will only be in the form of resonances with slightly broader dips than the dip, which would have been seen from a single resonance circuit. Only the resonance circuit(s) associated with the areas with deteriorated insulation will differ from the rest of the bundles and hence have shifted its/their resonance frequency / frequencies.

12 - Interpreting the shift of the resonance frequencies.

When we measure the Z(s) on a winding the first time, we neither know the resonance frequencies of the winding nor do we know the magnitude of Z(s). By the subsequent measurement, all of the resonances might well have changed/shifted, and the shifts in frequency will be a function of the wear. This function will most certainly not be linear. But the change in capacitance will be more or less inversely proportional to the change in the thickness of the insulation.

To find a rough correlation between the remaining insulation thickness (th) and the resonance frequency f_{Res} let us assume that:

> C as a function of the thickness th will be approximately proportional to $C = K /th)$ - and the resonance frequency $f_{Res.} = (2\pi)^{-1} * (LC)^{-½}$
> - where thickness is the remaining thickness of the wire insulation and K is a constant [F/m].

Thus: $f_{Res.}(th) = (2\pi)^{-1} *(LC)^{-½} = (thickness)^{½} / (2\pi\sqrt{KL})$.

$f_{Res.}(th) = (2\pi)^{-1} *(L*(K/th))^{-½} \Rightarrow f_{Res.}(th)^{2} = (2\pi)^{-2} *(L*(K/th))^{-1} \Rightarrow th \sim (f_{Res.}(th) /2\pi)^{-2} * / (L*K)^{-1}$

13 - Star- and Delta connected windings.

For three-phase machines connected in a star, it is sometimes difficult to get access to the star point.
And for machines connected in delta - when measuring between any two terminals - we have two other series connected windings connected in parallel with the one we want to check. A measurement between terminal A and B on a star connected machine will include the resonance frequencies of both Z_a and Z_b.

Likewise, a corresponding measurement on a delta-connected machine will include the resonance frequencies of both Z_a, Z_b and Z_c. Still, the shift in resonance frequencies of the resonances in the bundles formed by the capacitance of the worn insulation area(s) and the inductances of the other windings will be determined by the change in capacitance - and not in the inductance - and thus undergo the same percentage shift in resonance frequencies.

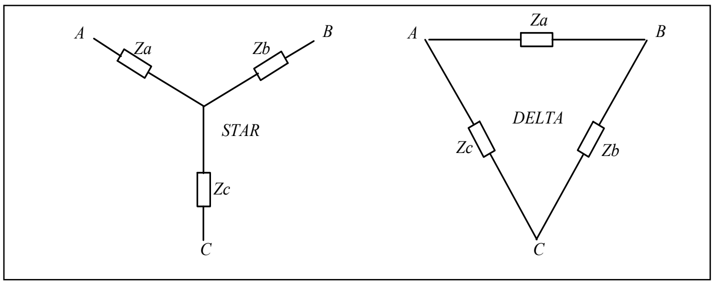


Figure 7. Star- and Delta connected windings in three-phase motors and three-phase transformers.

14 - Remote measurements on rotating machines.

For a technician it will be a major convenience, if the measurement on a motor could be done from the switchboard – and while the motor is operating - rather than by measuring at the motor terminals in the connection box of the motor.

According to NKT (which is a cable manufacturer) a typical 5 x 1,5-2,5 mm^2 cable has a capacitance between adjacent conductors of 130-160 nF/km, and from each conductor to “earth” of 210-280 nF/km. With 100 meters of 280 nF/km cable at 100 kHz the impedance of the cable comes to $Z = (\omega C)^{-1} = |56\Omega|$.

Thus, for bandwidth <100 kHz - and by comparing Z_{ab}, Z_{bc} and Z_{ca}- remote measurements (<100 m) seem feasible. However, if the dips in Z(s) are detected on bases of the phase angle of the impedance, the zero crossings of the resonances might be offset by the capacitance of the cable.

15 - Measurements on three-phase and single-phase machines.

For all three-phase electrical machines there are (at least) three windings, which are generally made by the same person(s) and out of the same batches of materials. (Like if you see your doctor for a swollen wrist, hand or other extremity, she will often say: “show me both arms” or “take off both your stockings” in order to compare the two of a kind). Likewise comparing the three (or more) windings will render similar important information.

For single-phase machines there are no other phases to compare with. Hence, the impedance Z(s)/propagation delay can only be compared to:

a. Former measurements done on the same machine - and/or
b. Other machines of same type/class.

16 – An alternative mean to detect a changing capacitance - measuring the propagation delay.

Changes in a winding can - as an alternative to the frequency domain - also be detected in the time domain in as changes in the propagation delay and / or in changes of reflections.

A transmission line can be emulated by a number of capacitances, resistors, inductors and conductivities. Comparing with figure 2, one realizes that the winding can be represented as a long transmission line with both inductance and capacitance continuously distributed along the wire.

The characteristic impedance of a transmission line is $Z_o = ((R + j\omega L) / (G + j\omega C))^{½}$.
(G is the conductance between the conductors per unit length; R is the resistance of conductors per unit length.)

The voltage reflection coefficient is: $\Gamma = (Z_r - Z_o) / (Z_r + Z_o)$.

For an ideal transmission line the phase constant $\beta = \omega (LC)^{½} = \omega/v = 2\pi/\lambda$.

For a low loss transmission line the approximate phase constant β

$$\beta = \omega\sqrt{LC} * (1 - RG/(4\omega^2 LC) + G^2/(8\omega^2 C^2) + R^2/(8\omega^2 L^2)).$$

(Source: Simon Ramo: Fields and Waves in communications Electronics Table 1.23 page 46.)

The R, G and L will remain virtually unchanged during the initial development of wear; only C will increase. For faults - originating from partial discharges due to holes in the insulation - G will be the primary changing parameter as carbon builds up in the holes in the insulations and between the turns. Partial discharges are however mainly associated with high voltage testing and are mainly seen in windings, which have already developed faults.

Hence the only remaining parameter to change due to wear is C. From the expression of the phase constant β it can be seen, that the phase constant will decline proportionally to $1/C^{3/2}$. The impact of G will require further investigations.

For a short circuit (i.e. $Z_r = 0$), Γ becomes –1. (I.e. the propagating waveform gets mirrored by a short circuit – please refer to figure 8). Hence, for $Z_r = 0$ the amplitude of the reflected voltage equals becomes the voltage of out-going voltage multiplied by -1. As the wave travels back from the short circuit - along the transmission line – the two opposite polarized wave forms will extinguish each other (see figure 8 below).

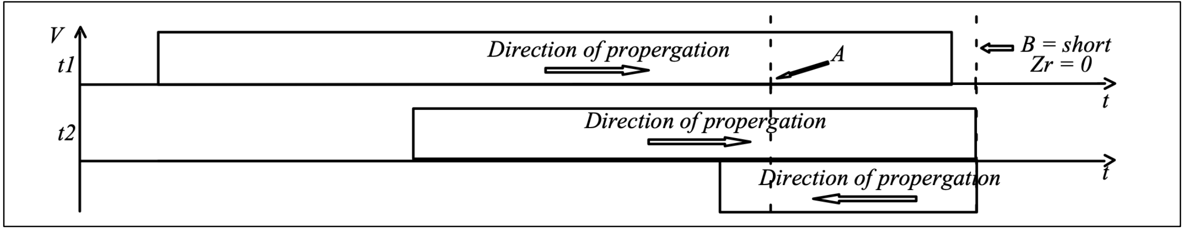


Figure 8. An out-bound traveling pulse shown at t1 and t2. Only during the time it takes the pulse to travel from A to B and back will there be a pulse to be seen in A.

Only for $Z_r = Z_o$ will there be no reflected wave traveling back. All other Z_r will cause reflections.

As the wear in a winding is generally restricted to a tiny fraction of the entire area of turns touching turns, so must the impact of the wear on the entire propagation delay be expected to be small. Hence, to detect wear of insulation in the time domain the measurements will presumably require a resolution in the range of nano second or sub nano second.

16.1 - Measuring propagation delay on a rotating machine connected in Delta.

When a unity step is imposed between terminal A and the chassis (of a motor connected in delta), and terminal B is grounded, then one out-bound wave will travel directly from A to B, where it will be reflected and return to A. When it arrives at A, a part of the amplitude will be extinguished. Another out-bound wave will travel from A, via C to B, where that too will be reflected and returned to A - both via C - and directly.

As was the case in the frequency domain for a non-faulty machines, the three phase windings will yield almost identical propagation delays. Hence, with B grounded, measuring the time delay between the pulse going into A, up to the first return of a reflected wave (A-B-A), must (for a healthy machine) equal half the delay of the pulse, which has travelled out and back via C (A-C-B-C-A).

And - for the wave, which went via C to B and then straight back to A (A-C-B-A) - it will have 3/2 of the delay of the first reflected wave (A-B-A). As an alternative to only grounding B, two of the terminals can (in turns) be shorted to ground, which – due to the symmetry - will simplify the deciphering of the reflections.

Hence, the propagation delay of each of the windings, can be extracted as the differences between the first, second and third main reflections. The reason for writing “main reflections” is, that the characteristic impedance of wire will constantly change along the winding, causing numerous reflections. Yet, providing a proper grounding of terminal B (and/or C), with a Z_r very close to zero, should generally provide distinct reflection times. Due to the differential time measurement, it seems feasible also to do the measurements from the mains end of the power cable of the motor - i.e. from the switchboard.

16.2 - Measuring propagation delay on a rotating machine connected in Star.

For the same measurement done on a star coupled motor, with both the B and the C terminal grounded, the signal will be divided into two signals at the star point. One part will travel to terminal B where it will be mirrored and travel back to the star point. The other part will go to the terminal C, where it will also be mirrored and travel back to the star point. Any discrepancy between the two propagations times will be seen at terminal A. If terminal B and C were left open ($\Gamma = +1$) the voltage would double at B and C.

17 - Comparing measurements in the time domain versus measurements in the frequency domain.

The Fourier transform states that what can be done in the frequency domain can also be done in the time domain. But one domain can be easier to deal with than the other. The previous paragraphs describing the measurements done within the time domain have been included to complement the description of the earlier description of the measurements done in the frequency domain.

Taking into account that it is only a small fraction of the entire capacitance, which will change during the development of the wear, it is clear, that it will only cause a minor change to the phase constant β.
Hence, the differences in propagation delay times will be correspondingly short – presumably in the nano- to pico-second range. This will call for RF (radio frequency) measurements in an environment, which is generally dominated by electrical noise (not least from switching inverters).

For my thesis at the Technical University I needed a sampling pulse of 300 ps. I generated the pulse by using a 1nF to short one end of a transmission line with a 150 ps propagation delay. An equivalent concept might be used for the winding tester to generate a test pulse for time domain.

I cannot exclude that there will be applications where propagation delay measurements would be preferred to measurements in the time domain. But I would recommend to start the project by focusing on the frequency domain where there are strong indications that the bandwidth can be restricted to an estimated 10-100 kHz, and thus much more user friendly.

18 - Functional Description of the Block Diagram.

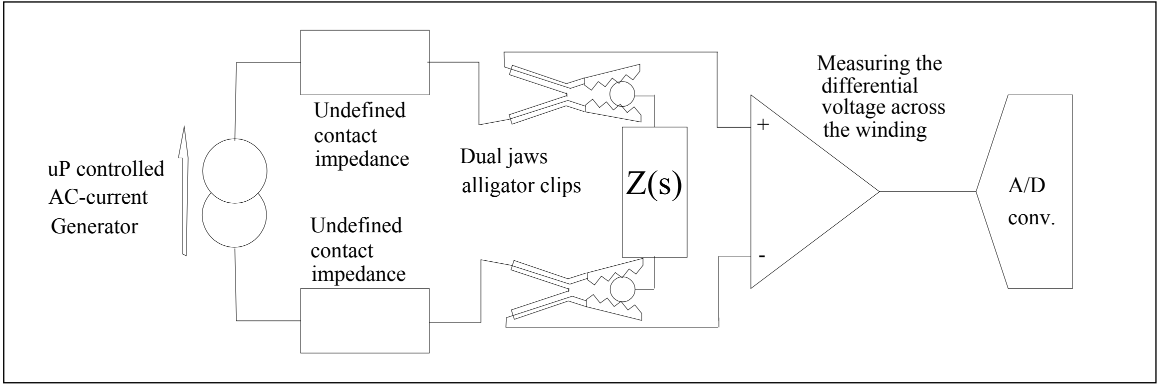


Figure 9. The concept of the four points measurement of the winding impedance(s) Z(s).

Figure 9 shows the proposed concept for measuring the winding impedance Z(s) as a function of the frequency with a four-point measurement. Left is the AC-current generator controlled by the microprocessor (uP) through a digital to analogue converter (= D/A converter - not shown). The undefined contact impedances represent both the impedance of the contact points (i.e. the alligator clips) plus the current limiting serial resistors and the DC-blocking capacitors.

In the case that noise from the mains and/or frequency inverters will appear to hinder proper measurements of Z(s), one remedy could be to narrow the voltage measuring bandwidth by applying a super heterodyne receiver to measure the voltage across the winding. Using a heterodyne receiver (where the frequency of the local oscillator is being locked to the sum of the frequency of the current generator plus the intermediate frequency), will allow for a much narrower bandwidth, and hence, an improvement in the signal to noise ratio.

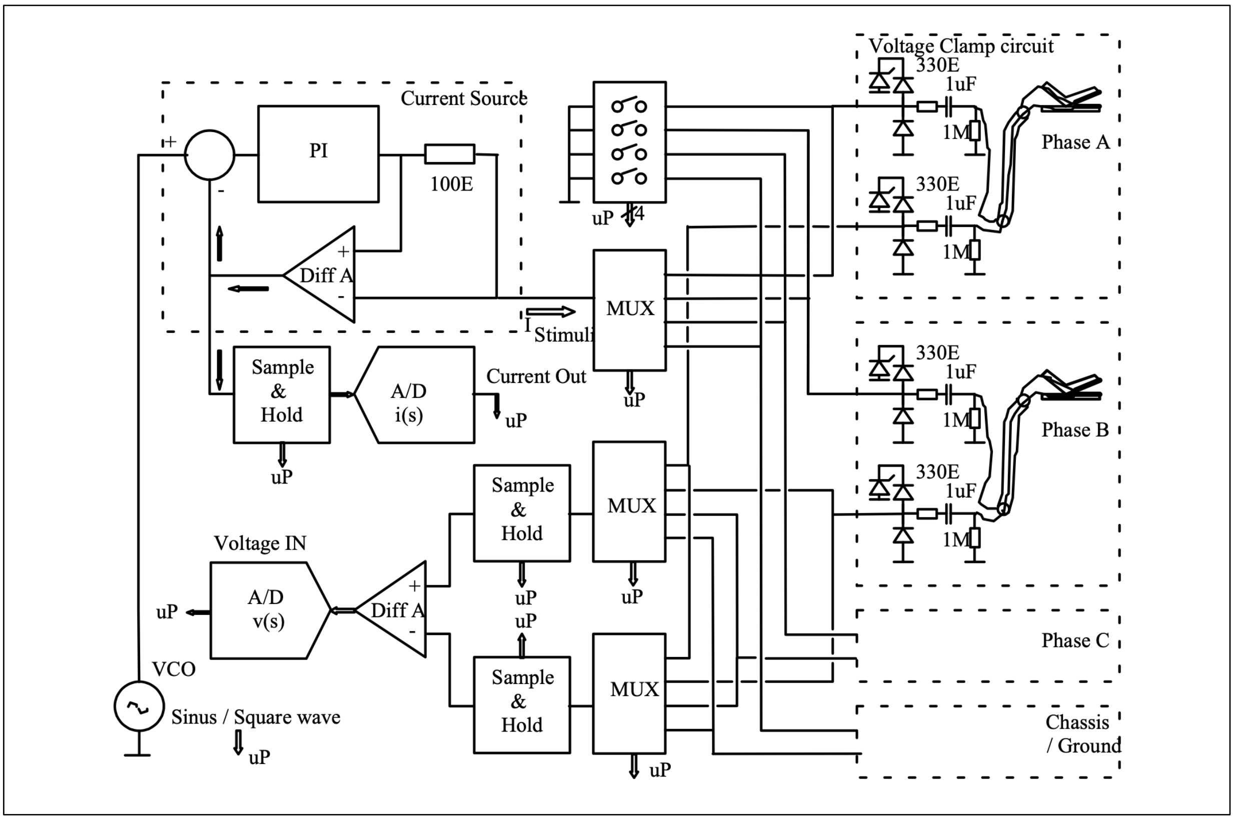


Figure 10. The Block schematic.

The block schematic in figure 10 is merely a suggestion as to how to implement the winding tester based on the Z(s) measurement shown on figure 9. In fact, it boils down to a four points AC impedance meter, where a current is imposed into- and through the winding - and the voltage across the winding is measured through separate probes. To spare the operator from keeping track of the phases, the circuit provides one probe for each of the three phases and one for neutral (or ground).

Top left on figure 10 is the current source with a PI closed loop (where the proportional part is considered needed to achieve the required bandwidth - estimated to 100 kHz or more). The current ($I_{Stimuli}$) is fed through the multiplexer (MUX). The impedances up to the alligator clip can be ignored as the current is imposed from a current source, which can be regarded as having an infinite impedance within the bandwidth of interest.

The top right array of switches is for shorting any of the probes (and thus winding terminals /or chassis) to the reference within the instrument. Thus, the impedance can be measured using any two of the four probes.

The current is fed to the winding through the clamping circuits. The function of the clamping circuit is to protect against inrush currents if / when the tester is connected to the mains power. The function of the capacitor is to block the 50Hz/60Hz mains frequency and the 1 MΩ is to safely discharge the capacitor. Dual contact alligator clips provide for 4 points measurements.

Supplying the current source through the shield of a coaxial cable and sensing through the center wire, allows the sensing wires to be capacitive decoupled relative to the signals to be measured. This causes the voltage of the signal wires to follow the voltage of the shields, hence minimizing the capacitive load / the impedance of the measuring probes at high frequencies. For the sake of safety, it might be considered to use the concept of floating inputs in a scope meter.

19 - The software/firmware.

I am not a software man, thus, the subsequent is merely what I see as the main tasks for the firmware within a portable winding tester. I envision the winding tester to be used either alone – or in conjunction with a laptop. If a specific piece of software will be needed on the laptop, that software might be comprised within the firmware downloaded in the winding meter. This will allow the user more freedom in the choice of laptop or PC to use for the measurements.

If the interaction between the winding meter and the laptop is designed and implemented in a seamless way, it will improve the user experience and the efficiency for the operator. A laptop will, due to the keyboard, often provide a graphical user interface with a better overview, a more responsive interaction and faster data entry. The connection between the laptop and the device should ideally work both with wireless technology, e.g. Bluetooth, or cabled, most likely USB".

The firmware tasks I envision are:

1. To measure and to calculate the impedance Z(s).
2. To find the frequencies where the phase angle of the impedance cross zero - i.e. the resonances.
3. To compare and point out the resonances, which deviates significantly from the rest.
4. To compare the resonances of the last recording to former recordings of the same machine.
5. To compare the resonances of the last recording to former recordings of the two other phases of the same machine and warn if the operator has inadvertently interchanged the probes and the terminals.
6. To load/display any three resonance recordings on to the screen.
7. To interface the instrument to the PC and a printer for the operator to display, compare and print out resonance recordings.
8. To monitor the battery condition.
9. To read the local temperature.
10. To handle any information / text about last resonance recording keyed in by the operator.
11. If a mains voltage is detected across the winding, to indicate on the display the 5th, the 7th, the 11th, the 13th and so on of the harmonics, where these harmonics are known to be able to blank out dips in the resonance frequencies.

As an example I have included some tentative steps in the first task:
"To measure and to calculate the impedance Z(s)." The implementation could be:

1. Reading the current amplitude from the memory and pass it on to a D/A (digital to analogue) converter, which determines the magnitude and frequency of the current imposed through the winding.
2. Read the data from the A/D converter, which measures the voltage across the winding, and pass that data on to the memory.
3. Calculate the magnitude of the impedance by dividing the peak voltage by the peak current.
4. Determine the phase angle of the winding impedance by comparing the zero crossing of the voltage to the zero crossing of the current and compare it to the period of the imposed current.
5. Generate a measurement file in which the magnitude and phase of the impedance of the winding is logged for a span of frequencies.

20 - The commercial issues.

I should emphasize, that I possess no formal commercial training.
But as a Jack of all trades I see the following four commercial applications:

1) Selling and buying information / experience in the form of measuring data to and from the customers of the winding tester.
2) Selling hardware in form of a hand-held winding tester.
3) Selling and / or leasing hardware in the form of stationary monitoring equipment (e.g. to wind farms).
4) Using the gained knowledge in production of electrical machines.

20.1 - Trading information and experience with the customers of the winding tester.

In the following R(wear) = a/b represents the ratio between:
a. The last resonance frequency to be recorded just before the break through in the winding insulation.
b. The initial resonance frequency recorded just after the machine was inaugurated.

At the start of the marketing of the winding tester a knowledge platform/experiences has to be established – both in the interest of the manufacturer and of the customers.
The information needed for both manufacturers and customers are correlations between: 1. the end of lifetime. 2. The ratio R(wear) and:

- a. The wire gauge.
- b. The current rating of the machine.
- c. The influence of inverter drives with and without filters.
- d. The runtime.
- e. Etc.

To prevent loosing image of being a trustworthy business partner, I will recommend the manufacturer to start the marketing by providing fairly conservative recommendations for end of lifetime values of R. As more and more experience on various types of transformers, motors, and drive conditions are collected or bought from the customers, the recommendations to end of lifetime values of R can be adjusted / extended. This will extend the customers' available use of their machines with a minimal risk of breakdowns.

This accumulation and redistribution of experience will be a win-win situation to both the customers and to the manufacturer – as:

- a. To the customers it will provide a better statistical base for their decisions as to how far they are prepared to allow the ratio R to drop before scrapping a machine.
- b. To the manufacturer as the big data provides knowledge about the parameters, which influences the wear of the machine and the correlation between the parameters such as inverter drives, current rating/wire gauges, R (wear) and the end of life.
- c. To the motor manufactures the gained knowledge will allow for better electrical machines.

This knowledge will also be of importance to the manufacturer when installing new stationary winding testers monitoring equipment, which has never before been monitored for winding wear.

The same knowledge can also provide valuable insight to the general aging process and thus to be used as a platform to further improvement in the manufacturers own manufacturing of electrical machines.

A database of good statistical value requires a high number of samples. Thus, it seems natural for the manufacturer to become the hub, around which this information should pivot - and to do so by asking/ offering the customers to collect the measured data, for the manufacturer to process the data and resell the processed data to the customers.

To the customers the collecting of data would be attractive if they could buy the updated database at a reduced price provided, that the customers in turn make their measurement data available to the manufacturer.
Thus, the more measuring reports the customer will submit - the better/more carefully the reports have been filled out – the lower price will be charged for the updated database.

For the winding tester, frequent software adaptions must be anticipated over the first years. If all customers will be granted free software updates, and the software in the winding tester is written to encourage, that the instrument must upload the measurements taken since its last update before the new software versions can be downloaded to the instrument, that will speed up the generation of an extensive database.

One might also find inspiration by the antivirus program companies, where the customers, while they download information on newly discovered viruses - also upload reports on their own virus encounters to the software company.

For the interpretations of the data in the database, it will be a major advantage to have the technical data for the electrical machines - and wherever possible - also data on their possible demise. This should be borne in mind while writing the software for the instrument, e.g. by requiring a minimum of technical data on the machine to be entered before a Z(s) graph can be stored, it is more likely that that information will be collected by the customers.

The concept of detecting insulation wear by measuring the Ratio R of the shift in resonance frequency, is virgin ground. Hence, new customers will naturally turn to the company, which can offer the biggest and most comprehensive database for an evaluation of the end of life / scraping value of R. This might be an incentive to start laboratory tests measuring and plotting R(wear) right up to end of life.

20.2 - Handheld winding testers.

The target group for a hand held instrument will be technicians and engineers in the monitoring, maintenance, trouble shouting and repair sectors.

The requirements for a typical technician will be a portable rechargeable battery operated instrument.
To minimize the risk of mistaking / interchanging the 3 phases and to allow for faster measurement set-up – four input channels – one for each of the three phases and one for neutral, all well marked - is recommended.

Further, an input for a power supply and a USB connector for connecting the instrument to a laptop – and possibly one extra USB connector for additional external memory to store measurement data in an USB stick, would be advantageous.

Hand-held instruments hold a large part of the market for instruments used by service technicians. Thus, in terms of marketing the winding tester to this target group, it might be attractive to ensure enhanced encapsulation. For this type of application, I would suggest an encapsulation rated for IP64 (meaning dust tight and protected against splashing of water) – or higher.

Note that for work done inside switchboards it is important for the instrument to be able to hang vertically.

20.3 - Stationary winding testers - permanently connected to the electrical machine.

I believe that in the long term the biggest market for the winding tester will be applications with a permanent installation of a stationary winding tester - where the cost and consequences of unexpected break down are particularly high – and hence, the customers are prepared to pay more for a permanent monitoring of the winding wear.

If the manufacturer could establish a market for the portable winding testers, that (to me) would be a natural stepping stone for introducing a stationary version of the winding tester.

Typical applications for a stationary version, which continuously surveys electrical machines could be:
Off-shore wind farms, utility transformers, motors in production lines and other electrical machines.
For the application in production lines it will be an important feature for a stationary winding tester to be able to carry out measurements on remote motors.

For plants where a stationary winding tester is to multiplex between a large number of machines (e.g. 10-1000 motors) the repetition rate/i.e. the frequency of the multiplexing, with which the machines are scanned, has to be considered and compared to the safety margin set by the R(wear) of the machine.

21 – Conclusion.
Based on the considerations described in the foregoing pages – and not least the associated environmental and economic benefits - I would recommend any potential manufacturer to initiate the development of a portable and a stationary "Winding Tester" based on the concept outlined in this presentation.

The described concept is considered to be novel and patentable; however, for obvious reasons no patent application has yet been filed. I would welcome an opportunity to elaborate on this matter personally.

Aarhus, Denmark, 27th March 2014

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PS. Patent issues.
In the time span from March 27th 2014 to February 17th 2015 I carried out an extensive search in patents. The outcome of this search was the following conclusion:

Closest to my concept comes M. W. Kending and D. N. Rogovin, "Method of conducting broadband impedance response tests to predict stator winding failure," U.S. Patent 6 323 658, Nov. 27, 2001.

However, its claims are limited to asynchronous machines – leaving synchronous machines and transformers uncovered. The patent was issued on 27th November 2001. The important issue is, however, that it expired on 19th. January 2010 due to failure to pay maintenance fees.

With the many differences between the adjacent patens and my concept and with the U.S. Patent 6 323 658 expired, it appears feasible to implement my concepts presented in "A Winding Tester – a New Means to Detect Wear in the Insulation in Electrical Machines" in one or more products.