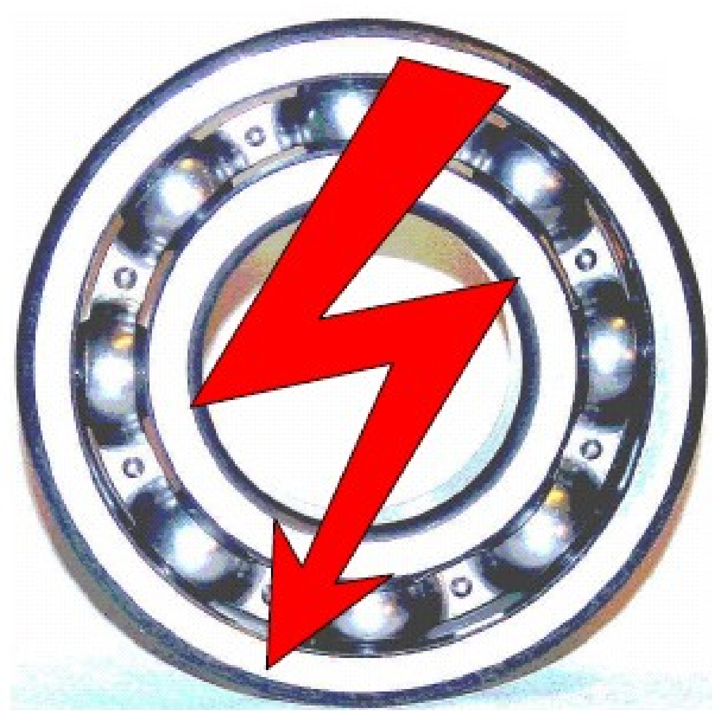
A practical introduction to Electric Discharge Machining, or ”Bearing Currents” in Bearings – what it is, how to diagnose, avoid and mitigate.

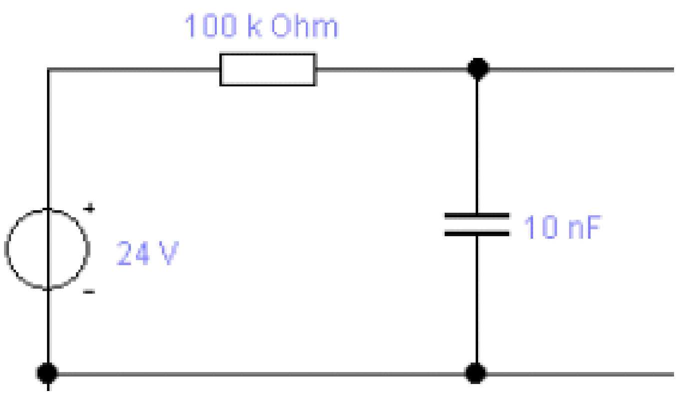


Contents

- Introduction. EDM, PWM.
- Bearing current damages – EDM – increase. PWM is the main cause.
- Problems exist in all motor sizes – more or less
- EDM close-up
- The four failure mechanisms
- Isolation, filter, shaft grounding, ceramic balls (hybrid bearings)
- EDM signature
- Cases

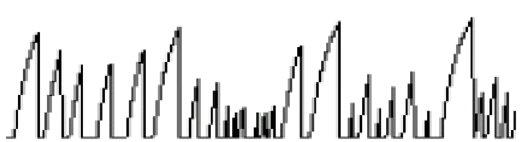
EDM – Physics and Reality

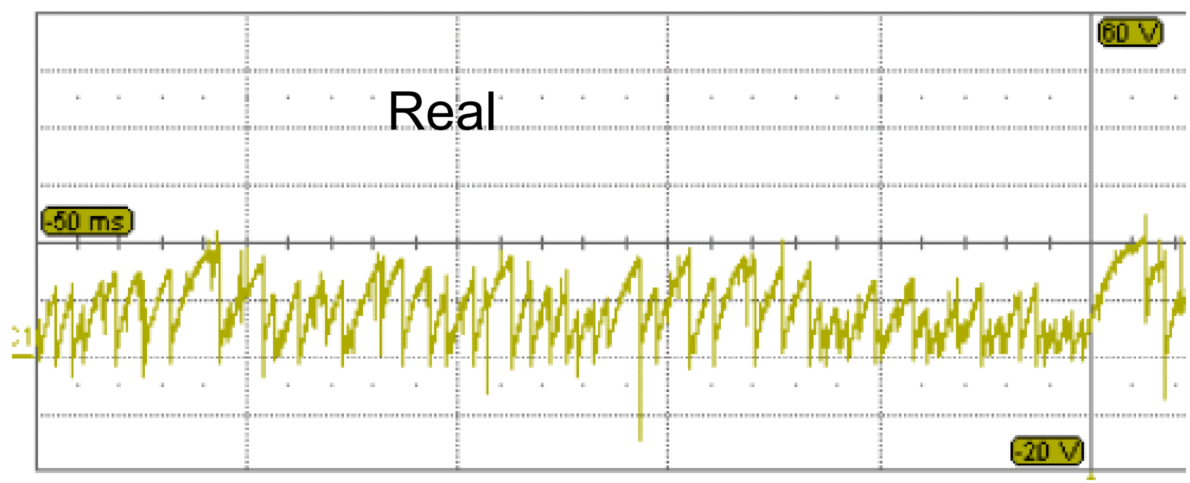
The oil film in a roller or ball bearing is quite thin – usually less than one micron. Two conditions determine break-down voltage: Oil film thickness and stochastically occuring impurities in surfaces and oil.



A simple test circuit can be used to study break-down voltage. See figure to left. Results shown are simulated performance and measurements on a real 6214 DGBB.

Simulated

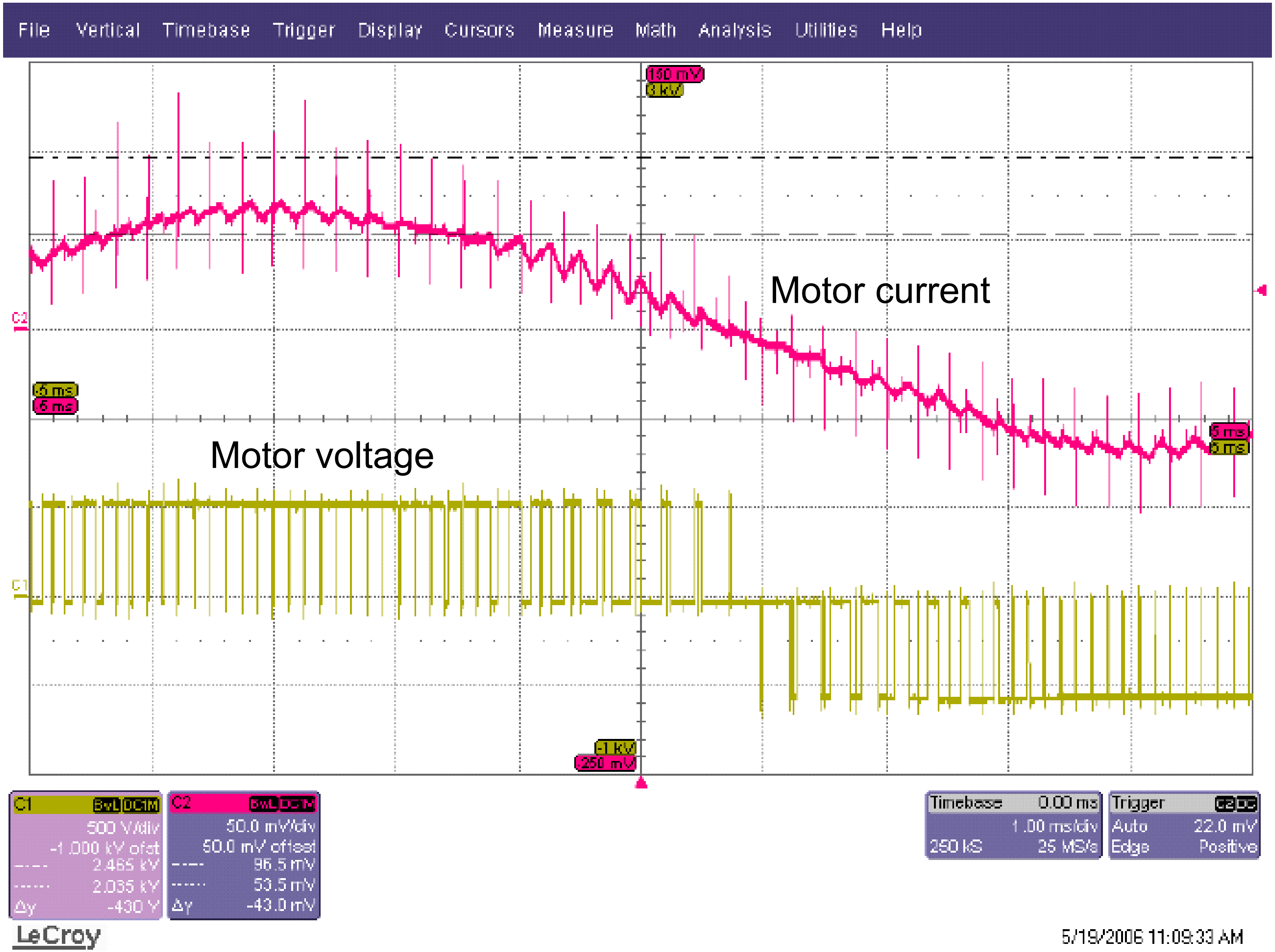




It is very rare that you find a bearing with a DC voltage applied to it like shown in previous frame. The voltage does, of course, come from other sources. But the DC break-down test illustrates what an EDM break-down is and it is a good starting point for the following discussion.

The most common source of shaft voltage is now parasitic coupling from the stator of PWM fed asynchronouos motors. An example of a PWM voltage and the resulting motor current is given in next frame.

EDM – Physics and Reality



Bearing damages increase – PWM is the culprit

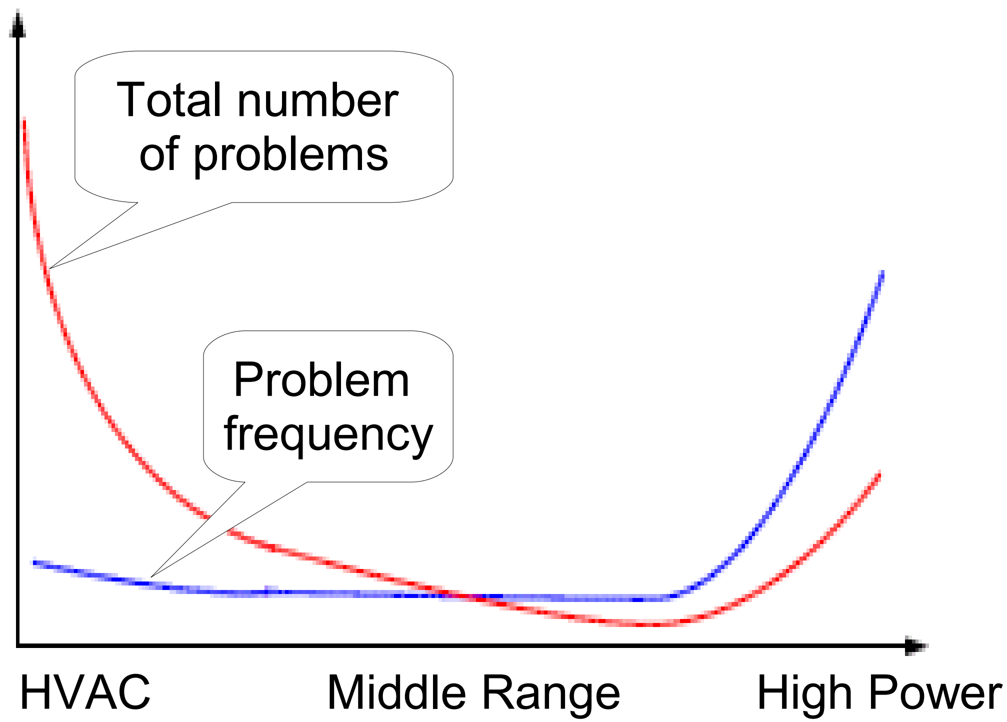
There are a few reasons for electrical damage to bearings.

The more common are:

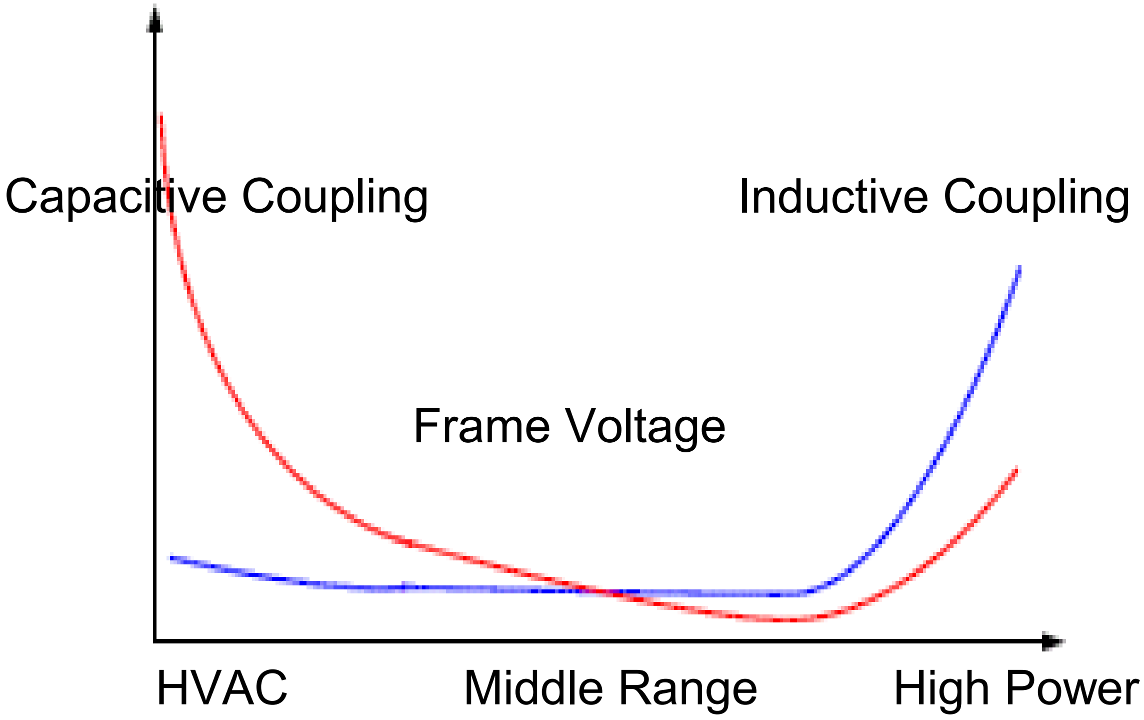
- Electric welding with common lead applied to wrong spot
- ”Locomotive grounding” through bearings
- Circulating current through shaft and bearings
- Electrostatic discharge (EDM) through bearing

Increased use of VFDs with PWM increases EDM and is now the dominating reason for bearing damages

Problems exist in all motor sizes – not only large ones.



Different problems in different motor sizes



EDM Close-up

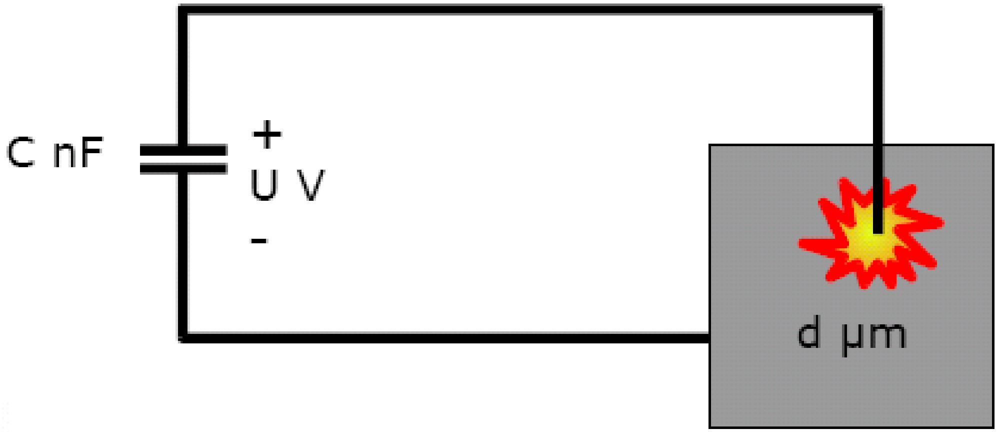
There are four prerequisites for EDM (Electric Discharge Machining)

- Capacitance
- Charge (voltage across capacitance)
- Isolation
- Isolation failure

EDM can be avoided by eliminating one (or several) of these prerequisites

EDM Close-up

Energy in the arc evaporates steel so that a crater is created.

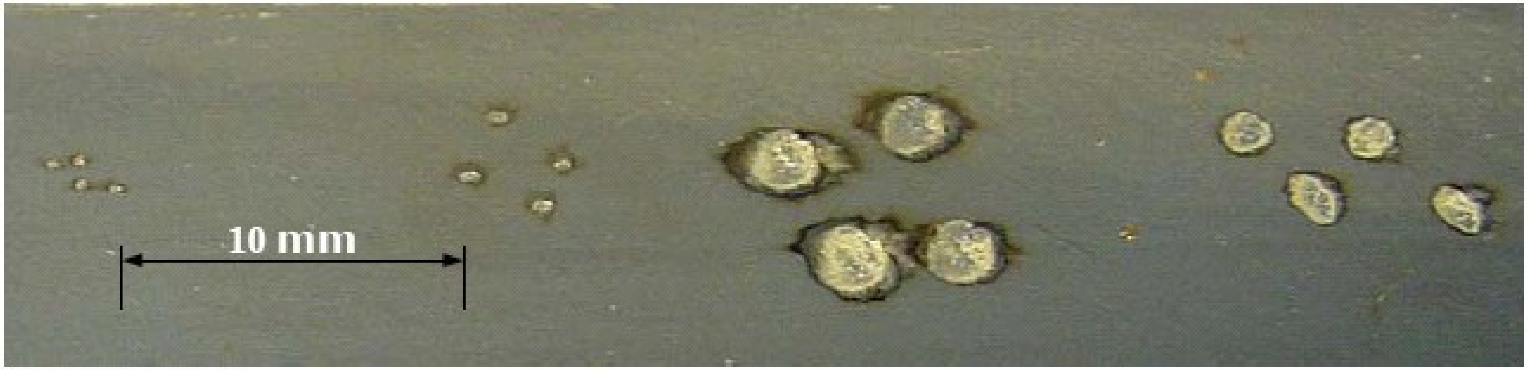


$$d = k(U^2C)^{1/3}$$

k ≈ 0.1 when units are µm, V and nF

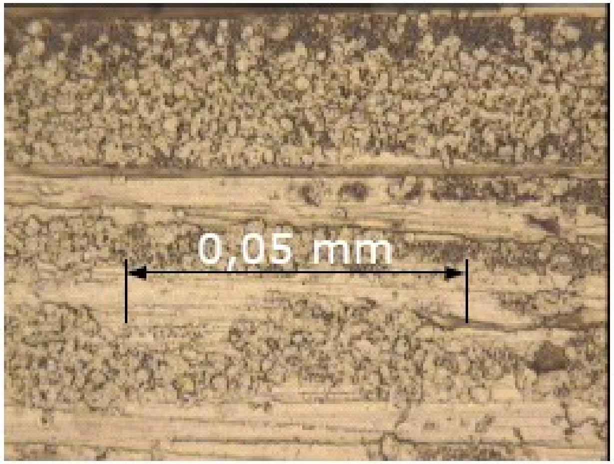
EDM Close-up

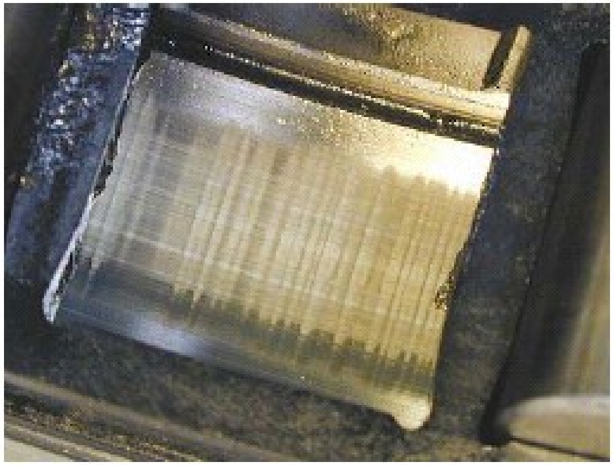
Test with ”macro-energy”. Microfarads and hundreds of volts produce shallow craters. But the principle holds – more capacitance and more voltage create larger craters



EDM Close-up

Normal capacitance values (1 – 10 nF) and normal voltages (5 – 15 V) produce craters in the 1 micron range. Those shown to the left are about that size.





Typical wash-board pattern shown to the right. The pattern has no connection to inverter frequency or speed – a popular and common misunderstanding

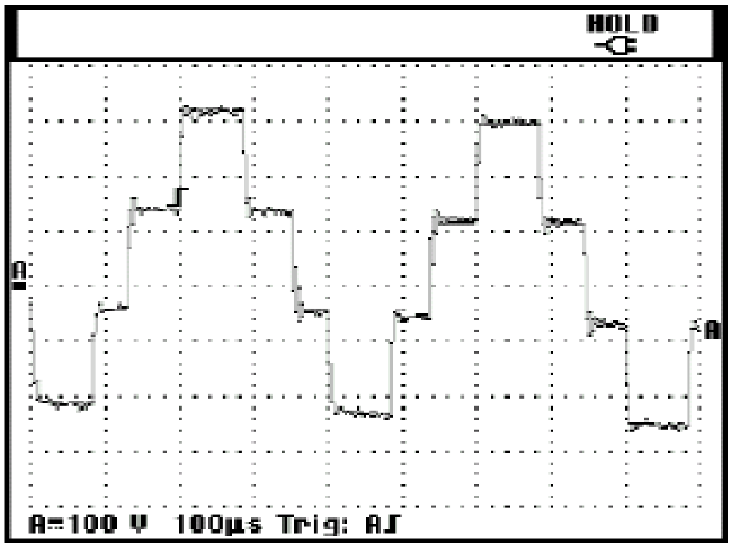
The four failure mechanisms

EDM requires that there is a potential difference across the bearing – in other words; there shall be a voltage difference between rotor and stator. This voltage difference can be created in four different ways:

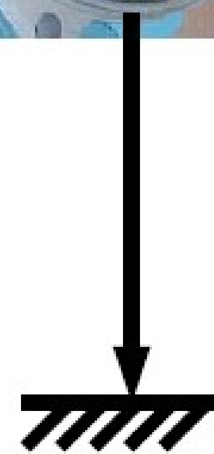
- Capacitively coupled
- Inductively coupled
- Frame voltage due to high ground impedance
- Externally coupled energy

We shall have a closer look at these in the following frames.

The four failure mechanisms – 1. Capacitive Coupling.



M11
CMV. Stjärnkopplade 50 kohm motstånd. Mittpunkt – jord.

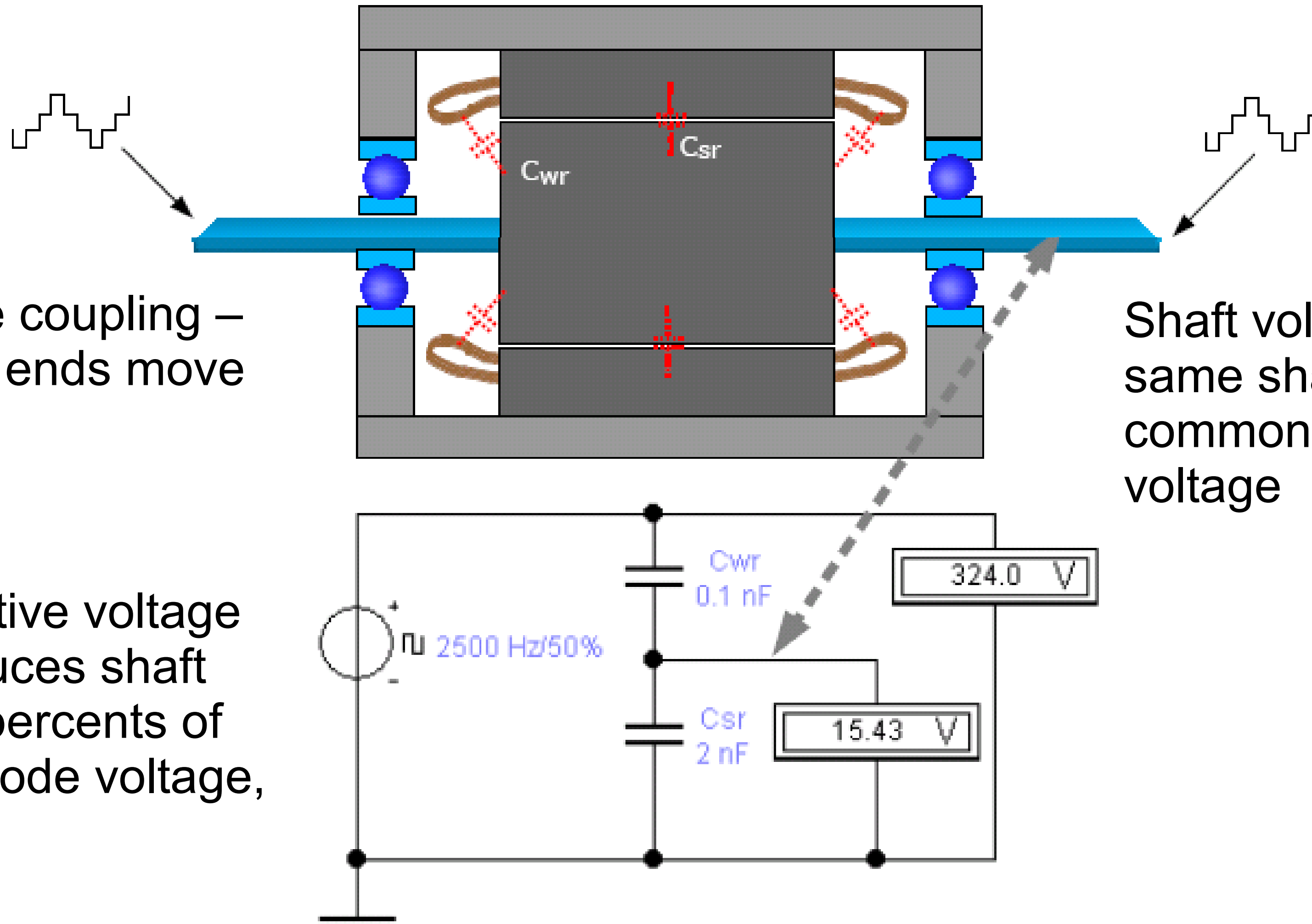


PWM voltage from the VFD has very steep edges.

The common mode voltage (left) is capacitively coupled from stator to rotor. The resulting voltage across the bearing results in EDM and destruction.

The four failure mechanisms – 1. Capacitive Coupling.

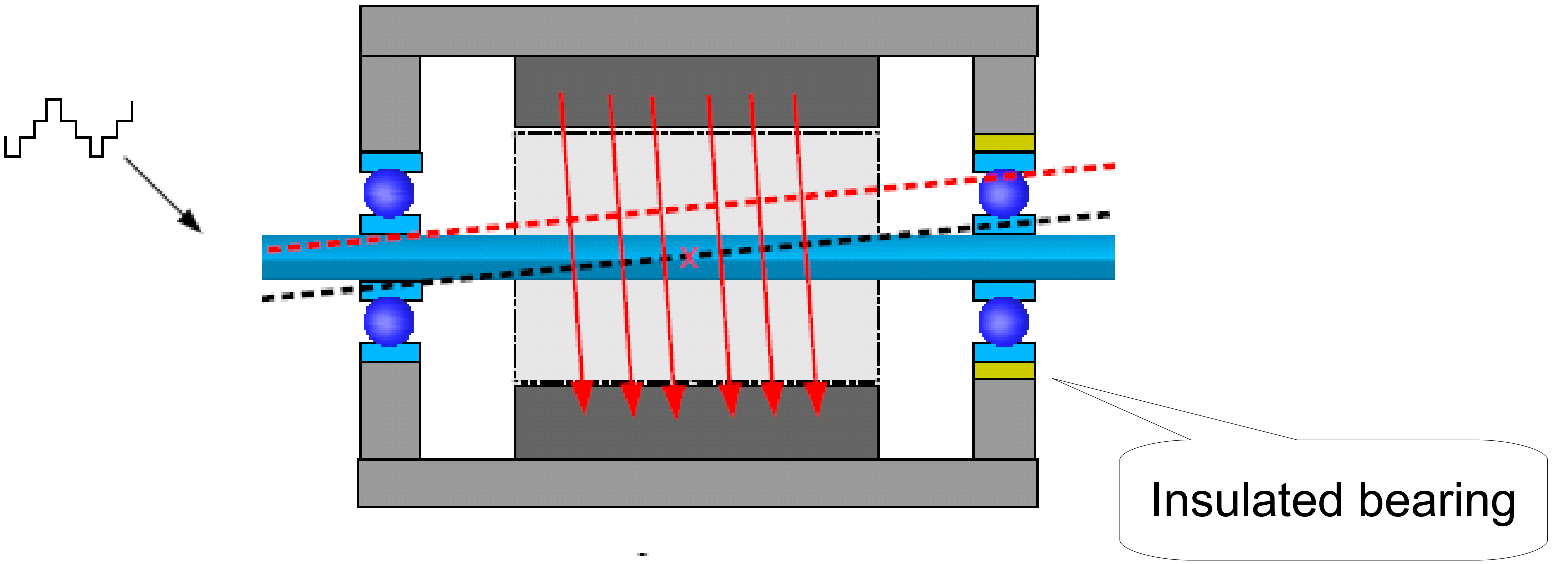
Capacitive coupling – both shaft ends move in-phase.



Shaft voltage is same shape as common-mode voltage

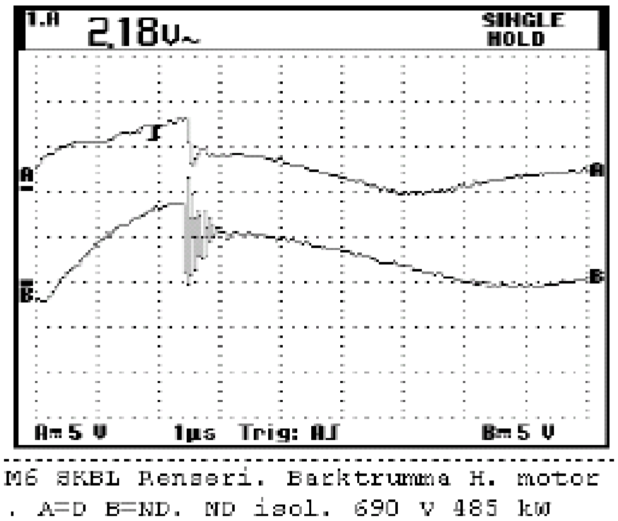
The capacitive voltage divider reduces shaft voltage to percents of common-mode voltage,

The four failure mechanisms – 1. Capacitive Coupling.



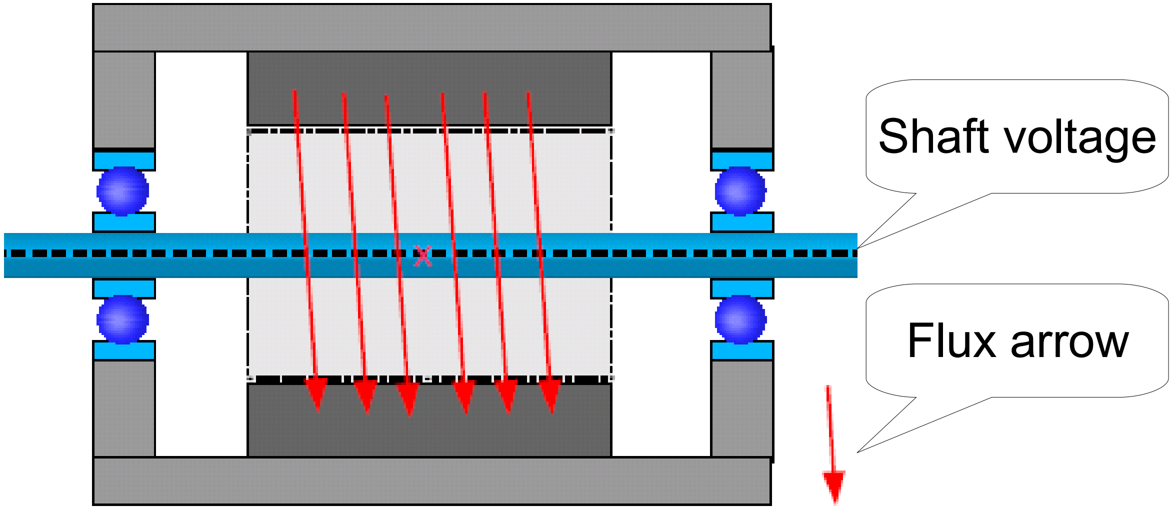
One insulated bearing (or one hybrid bearing) is of no use in a situation like this. The result is that rotor discharges in the other bearing.
The bearing with the lowest break-down voltage (varies stochastically over time) breaks down first. If there's only one bearing, the ”earliest” break-down voltage gets higher. And, since energy is proportional to voltage squared, discharge energy – and damage – increases.

The four failure mechanisms – 1. Capacitive Coupling.



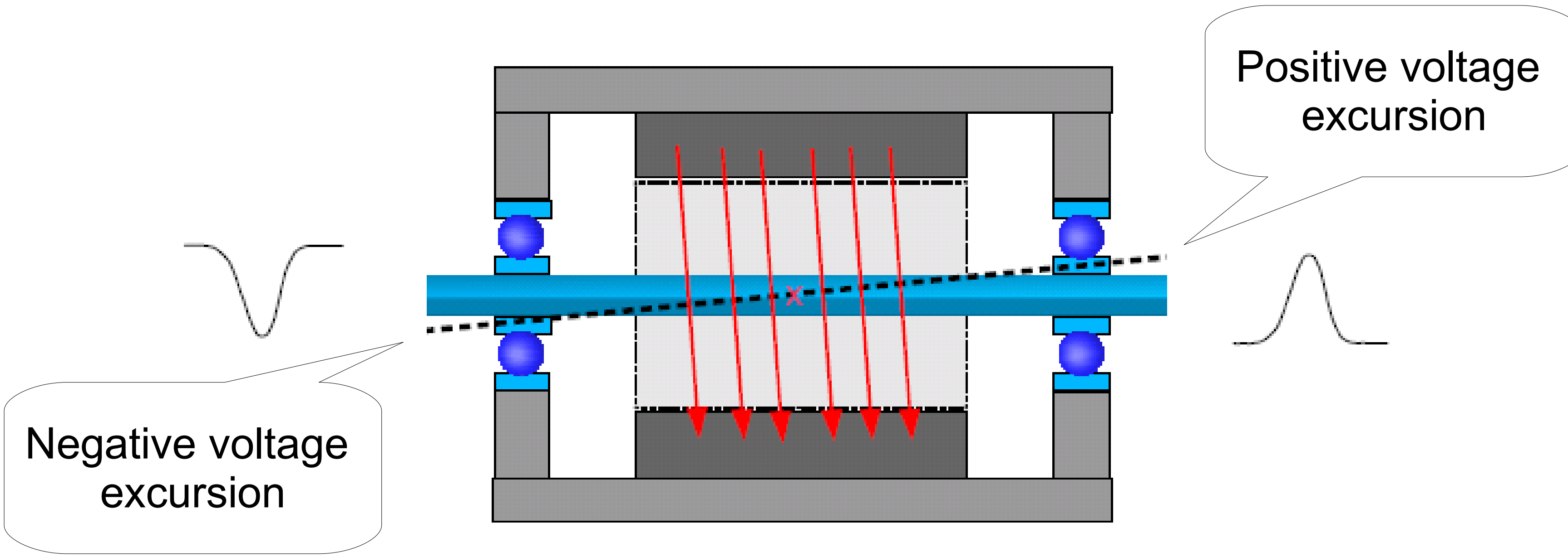
An example of capacitive coupling. This is a non-typical case in a rather large motor. The fact that both shaft ends are in-phase is important. The ND bearing is insulated. This means that the shaft voltage doesn't go to zero and stays there, but oscillates with a high frequency determined by bearing capacitance and ”local” inductance. The rotor inductance and capacitance act as a lowpass filter – the oscillations can hardly be seen in trace A.

The four failure mechanisms – 2. Inductive Coupling.



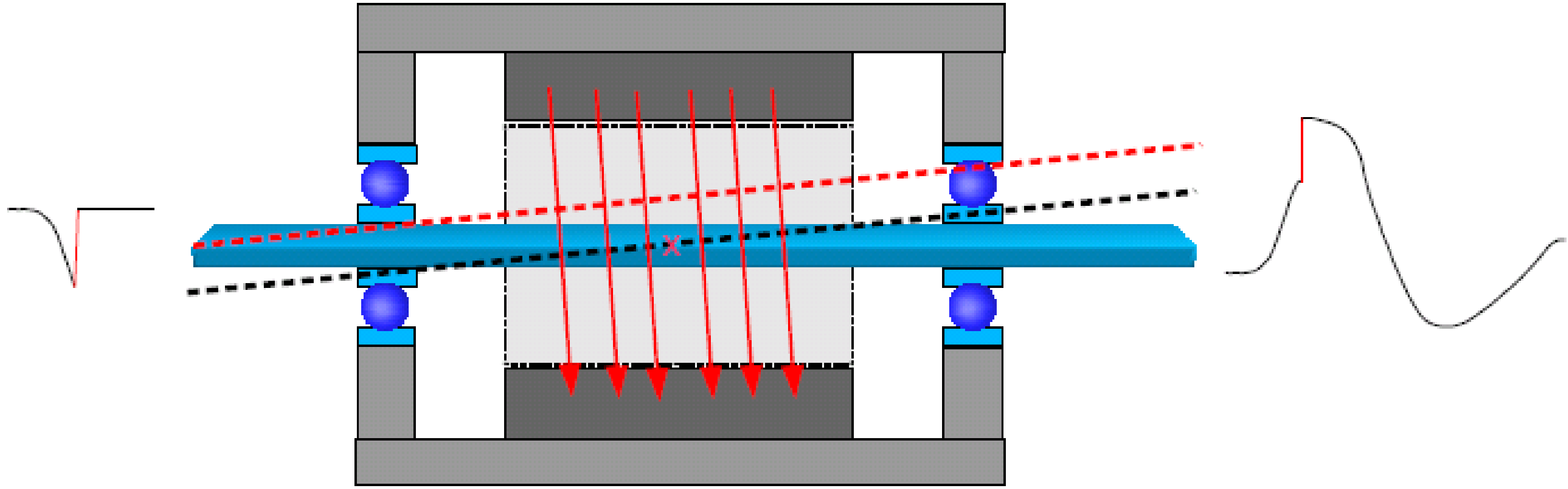
The sum of the three phases that make up a PWM voltage does not equal zero. A resulting non-zero stray current is going from stator winding via capacitance to ground. The stray current invokes a magnetic field that (contrary to the sine field) induces a voltage in the motor shaft. A voltage that can reach 60 V pk or more in large machines. The shaft end voltages move out of phase.

The four failure mechanisms – 2. Inductive Coupling.



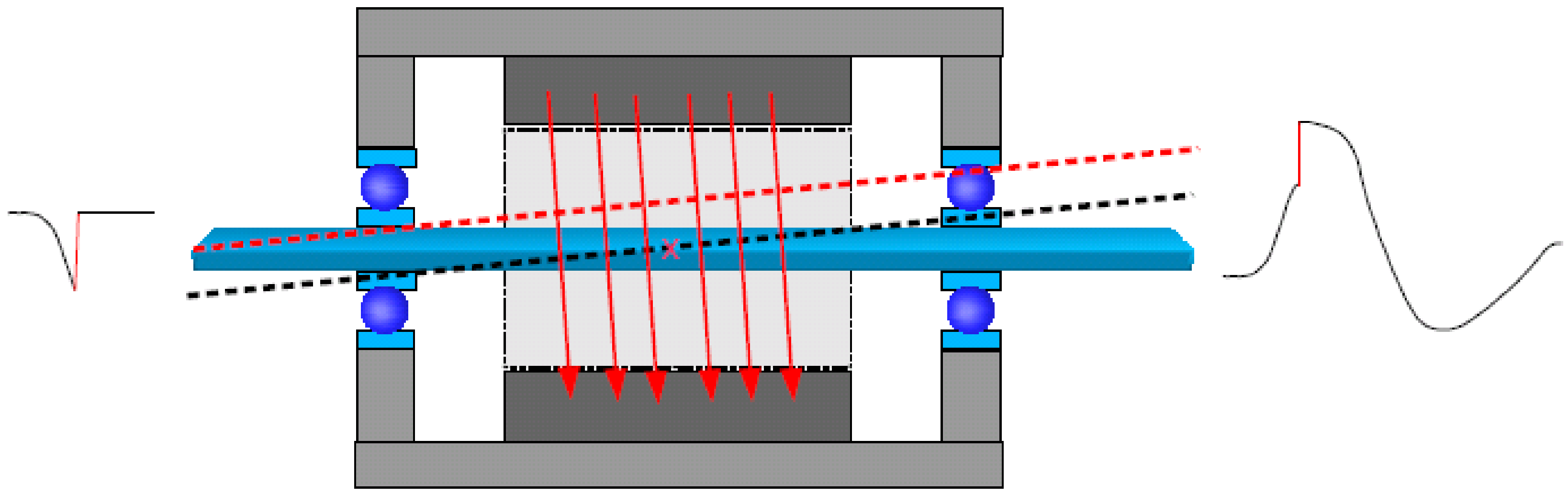
Shaft mean voltage is zero. Excursions usually go to tens of volts. Pulse width is in microseconds range. RMS voltage, therefore, usually is below 1 V. Multimeters can not be used to study shaft voltage. Use an oscilloscope with at least 20 MHz band-width.

The four failure mechanisms – 2. Inductive Coupling.



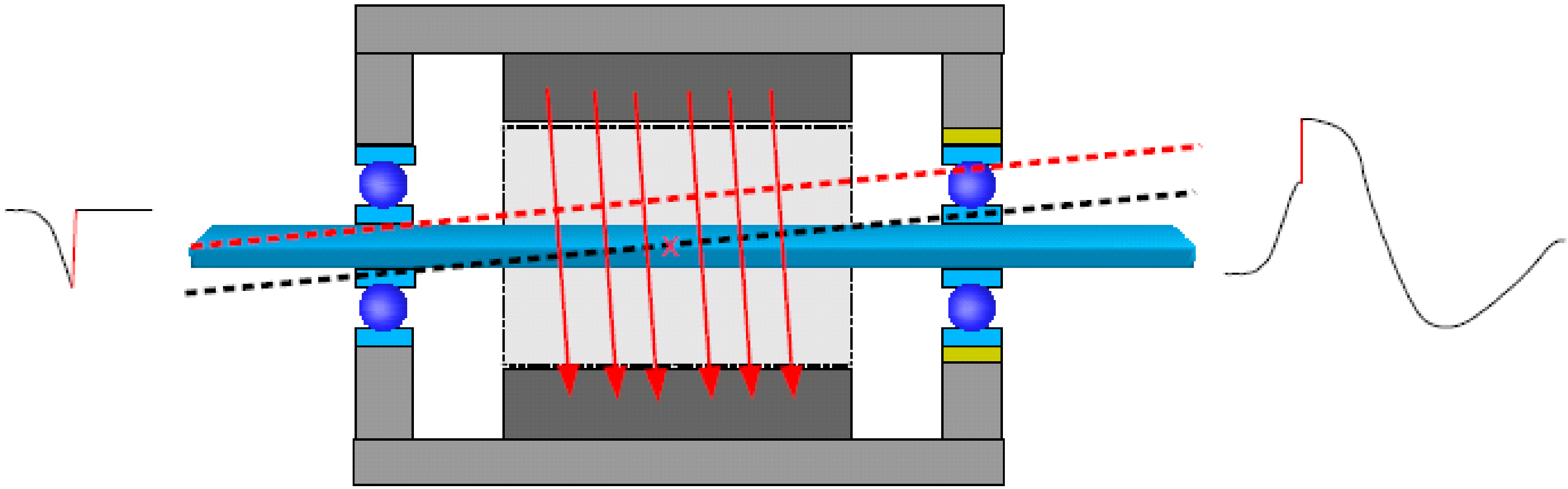
A typical PWM EDM situation. Left shaft end goes negative until a break-down occurs. Left end then moves in positive direction to zero volts. In fact – the whole rotor and shaft moves in positive direction so that the right shaft end goes even higher than it was. Sometimes causing a secondary break-down in that bearing.

The four failure mechanisms – 2. Inductive Coupling.



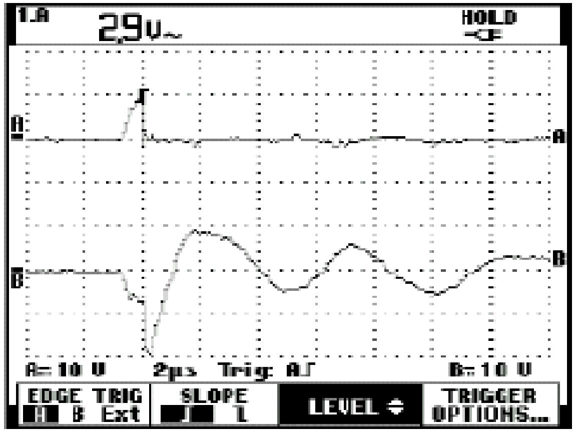
Rotor capacitance is a key parameter. Even with a completely insulated right end bearing, the voltage excursion at the left end would be the same – and also the resulting break-down.
An insulated bearing is usually effective only in the ”old-fashioned” magnetic imbalance situation. That is not a very common situation in modern motors with today's tight maufacturing tolerances.

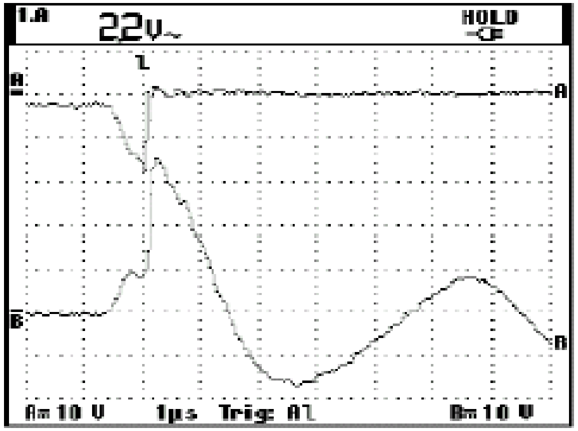
The four failure mechanisms – 2. Inductive Coupling.



An insulated bearing has been installed (yellow = insulation). As shown, the left bearing does not ”know” that there is an insulated bearing. The voltage excursion is same as before and break-down also. Current is NOT circulating in shaft – it is only a question of discharging rotor capacitance. But, the insulation usually prolongs service life of the insulated bearing. Not the non-insulated.

The four failure mechanisms – 2. Inductive Coupling.

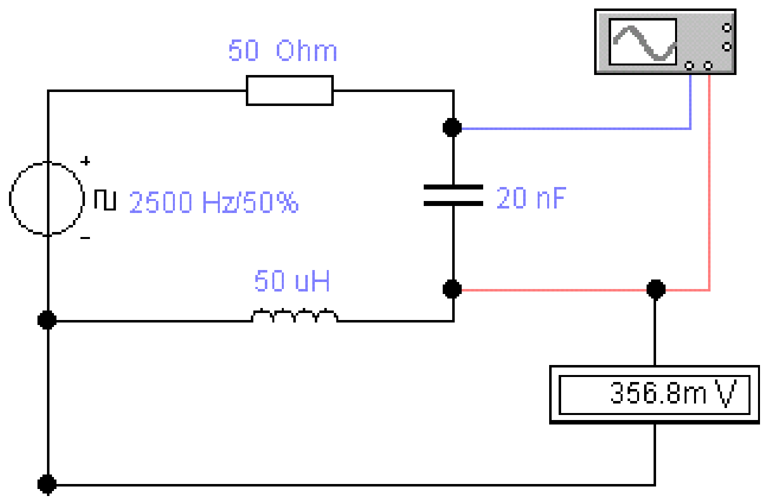




Examples of shaft voltages – inductive coupling.

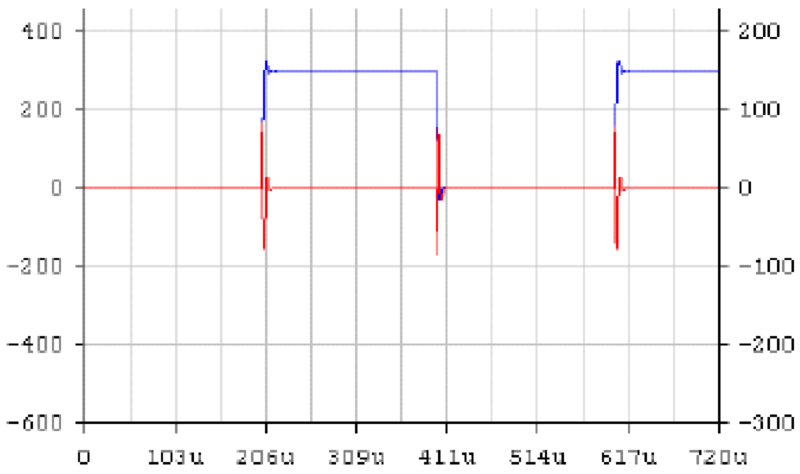
The fact that the ends move in opposite directions is a sure sign that we have inductive coupling. The break-down in upper trace is reflected in a similar voltage decrease/increase in lower trace.

The four failure mechanisms – 3. Frame Voltage.



Simulation. PWM edges are coupled via 20 nF to motor frame. PE inductance (50 μH in this case) produces voltage drop and ringing.

Blue = PWM.
Red = Frame Voltage.
The TRMS voltmeter shows a few hundred mV. The scope shows true voltage.
Good grounding is important in cases like this.

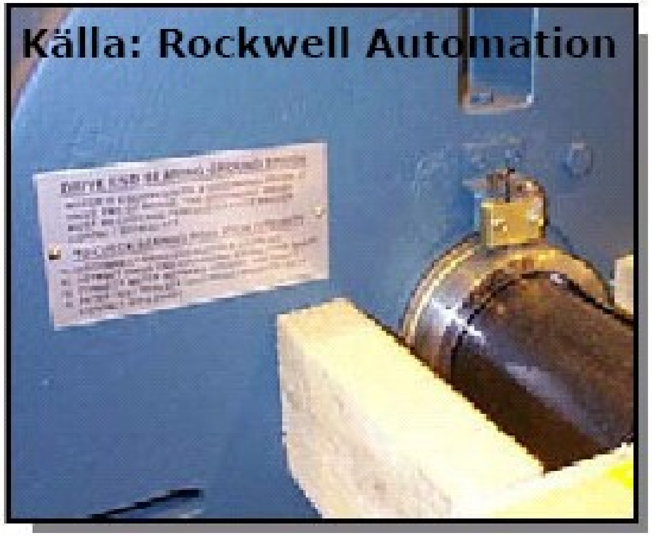


The four failure mechanisms – 4. External Energy.

External energy is almost always triboelectric energy – or static electricity. Triboelectricity is what you get when rubbing two materials against each other. Think Cat skin and Ebonite. Insulating oils and sometimes even air can produce static electricity. Lightning is a good, although somewhat exaggerated, example. Situations that CAN produce triboelectricity are:

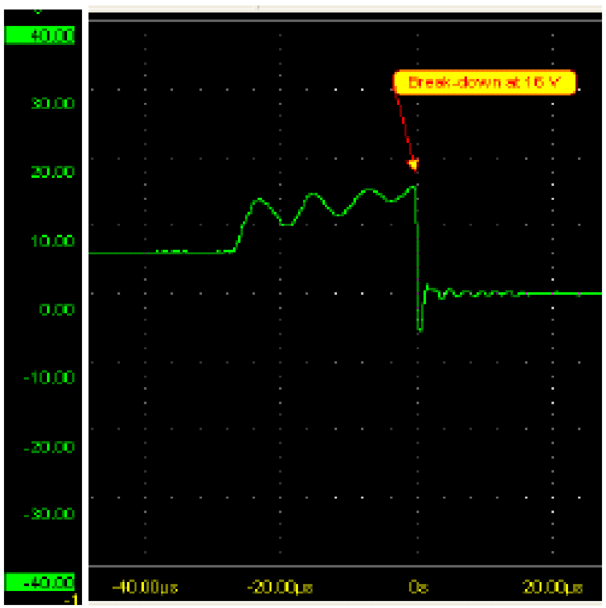
- Belt drives
- Pumps and filters for oils. Synthetic oils are critical.
- Fast (direct driven) fans.
- Situations where dy material is conveyed. Wires in paper machine dryer sections is a practical example.
- There are indications that Wind Turbines may have this problem.

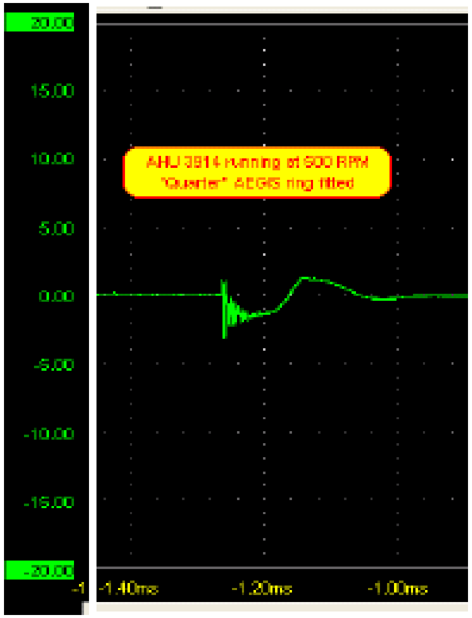
Mitigation – Grounding Brushes



Grounding brushes create a parallel current path so that the bearing is saved. Not only that – they also prevent that a charge is formed. Grounding brushes are often very effective, but some expertise may be needed when applying them to large machines. They can be purpose-built units like the Rockwell example – or simple ad hoc devices like the one to the right.
They need care, inspection and maintenance.

Mitigation – Grounding Brushes



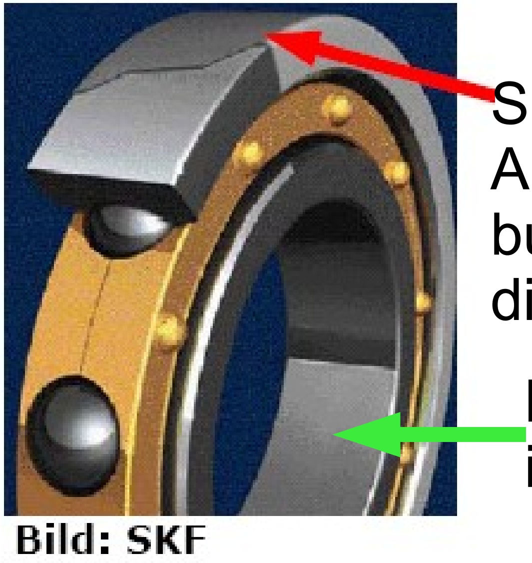


An interesting solution is a new type of shaft grounding ring with carbon fibers. A test was made to see if they are as efficient as the manufacturer claims. The motor was a 25 HP motor fed from a well-known drive with 8 kHz carrier frequency. This particular test was made with a quarter of a ring. The EDM shown to the left is completely eliminated. The residual voltage is below 2 V, which is well below EDM inception voltage. Note: Different scaling!

Mitigation – Insulation

Modifying end shield so that bearing is insulated is one method that has been used. It is rather costly, but standard bearings can be used – no need to stock specials.

Mitigation – Insulation

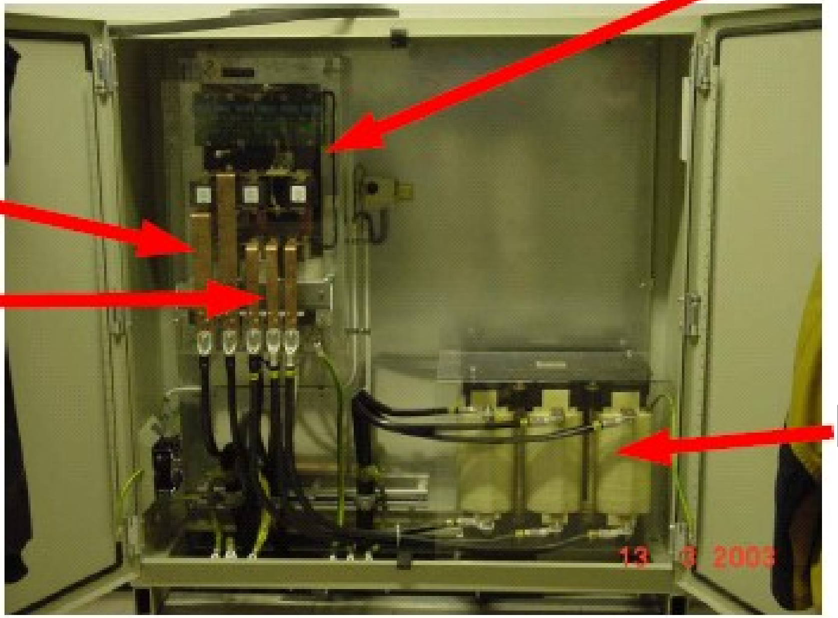


Sputtered Al2O3. A good insulator, but also a good dielectric.

Better put insulation here

Al2O3 (Alumina) is a good insulator, but also a good dielectric. Capacitance can get rather high – in the 10 nF range for a 70 mm ID bearing. Putting the insulation on the inner diameter has several advantages. Less capacitance and also thermal insulation from hot rotor/shaft. And better thermal contact with end bell.

Mitigation – Filters



dv/dt filters reduce the PWM edge's rate-of-change. That effectively reduces capacitive stray currents,which means less EDM. This is a Siemens type filter. It is rather elaborate, transient energy is fed back to the DC link of the inverter (that's what the diodes are for) and capacitors make sure that the specified V/µs isn't exceeded.

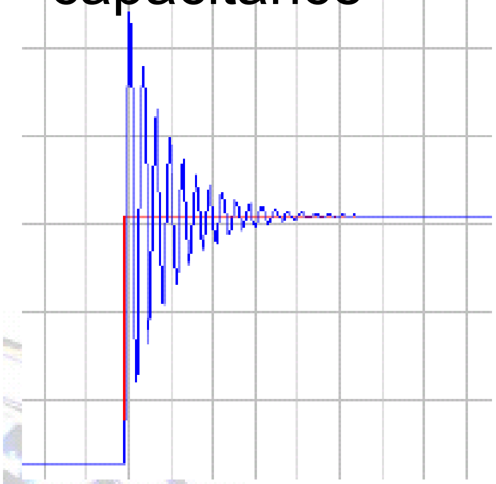
Mitigation – Filters

ABB, among others, have a simpler filter. It needs a cable and motor capacitance to be effective. Ringing is avoided by shunting with resistors. This filter is for a smaller machine than the Siemens filter shown in previous picture.

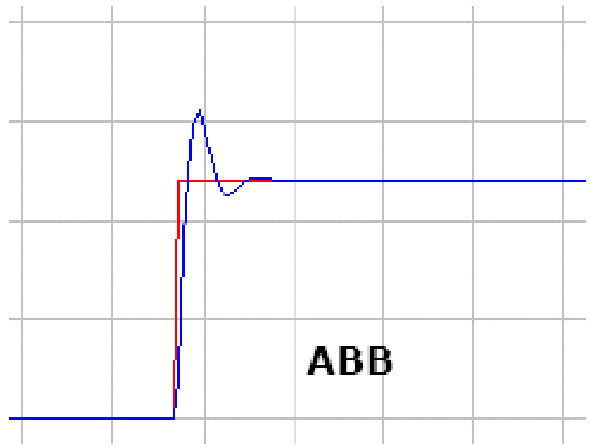
Mitigation – Filters

Different dv/dt filters produce different wave-forms.

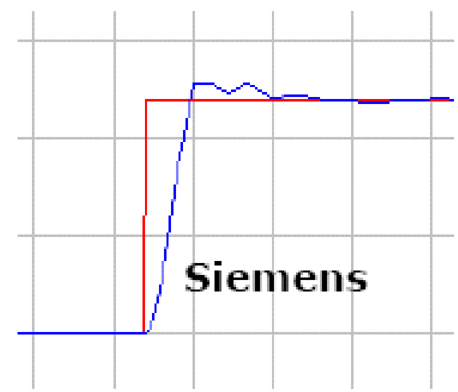
No damping – only reactor and cable capacitance



Damping resistors

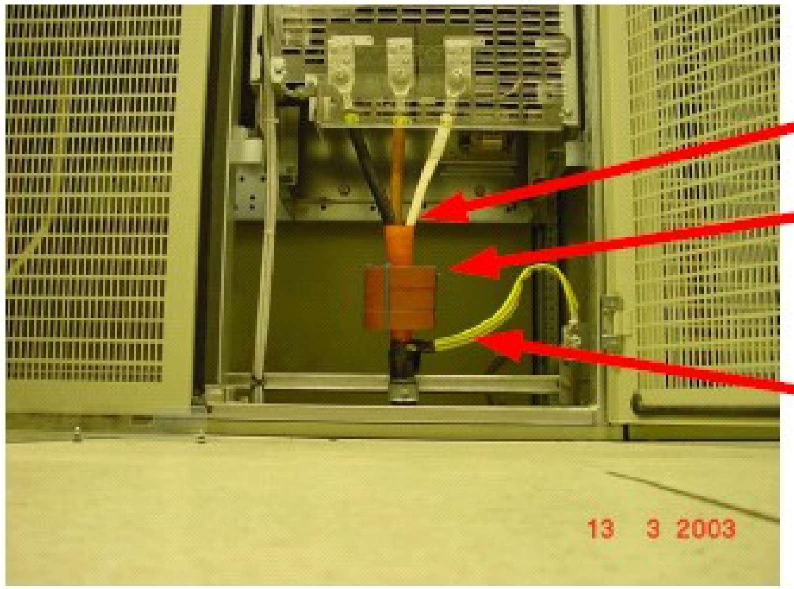


Energy in ringing fed back to DC link.



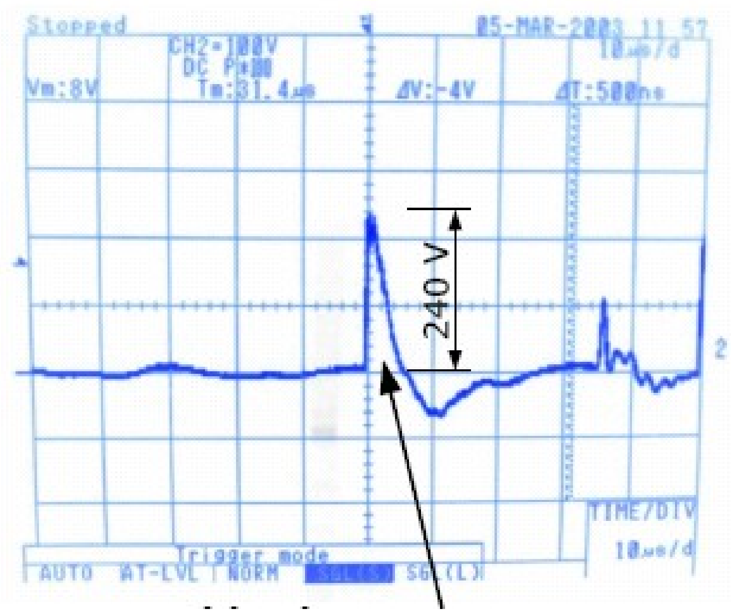
Red = VFD output   Blue = motor voltage

Mitigation – Filters

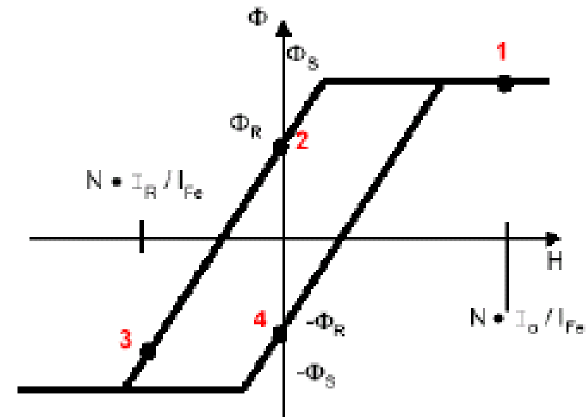


A Common-mode filter (ABB shown) consists of a set of ”Metal Glass” toroids. The toroids are highly permeable and represent a high impedance to common-mode currents. They do so by absorbing the steep edges of the PWM. That not only reduces capacitive stray currents, but also frame voltage. It is an effective solution, that sometimes needs to be supplemented by insulated bearings.

Mitigation – Filters



Three toroids can absorb 600 µVs



Material data of VITROVAC 6025Z:

	typical values
Saturation flux density (25 °C), B_s	0.58 T
Bipolar flux density swing (25 °C)	1.15 T
Bipolar flux density swing (90 °C)	1.0 T
Squareness, B_r / B_s	> 95 %
Saturation magnetostriction (25 °C)	$< 0.2 \times 10^{-6}$
Curie temperature, T_c	240 °C
Continuous upper operation temperature	90 °C

Amorphous soft magnetic material has very good magnetic properties. That is also true for some iron powder rings. Ferrites have much lower permeability and do not perform well. The term ”Ferrite Ring” is often used to describe these non-ferrite toroids.

Mitigation

Drive system manufacturers often provide good advice. This is from the Rockwell Automation site.

REMEDY	Well terminated cable ground connec-tions: drive to motor	Bonding strap between motor and load frame	One insulated motor bearing on opposite drive end	Two insulated motor bearings	Shaft grounding brush across one motor bearing	Faraday shield (ESIM)	Insulated coupling between motor and driven load
Source of Current							
Internal, circulating, due to magnetic dissymmetry leading to net flux linking shaft (fundamental frequency or sine wave). Generally occurs on motors above NEMA 400 frame. *Figure 2*			X	X	Avoid without opposite bearing insulated		

Mitigation

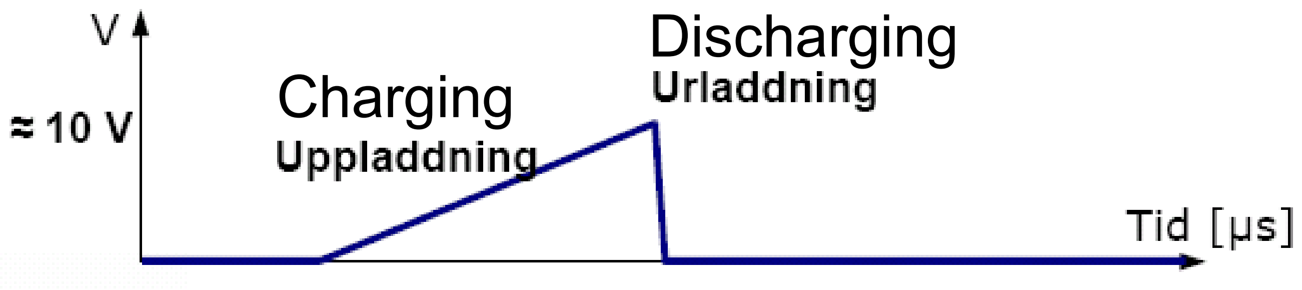
REMEDY	Well terminated cable ground connections: drive to motor	Bonding strap between motor and load frame	One insulated motor bearing on opposite drive end	Two insulated motor bearings	Shaft grounding brush across one motor bearing	Faraday shield (ESIM)	Insulated coupling between motor and driven load
Common mode (ground) current (induced by common mode dv/dt) taking a return path via the motor shaft extension and coupled equipment. *Figure 4 – gold current*	X	X		X	Avoid without insulated coupling or bonding strap between motor and load to protect driven equipment		X

Mitigation

REMEDY	Well terminated cable ground connec-tions: drive to motor	Bonding strap between motor and load frame	One insulated motor bearing on opposite drive end	Two insulated motor bearings	Shaft grounding brush across one motor bearing	Faraday shield (ESIM)	Insulated coupling between motor and driven load
Discharge through bearing of capacitively-coupled common mode voltage (scaled by capacitor divider). *Figure 4 – red and green current*		Only if in combination with motor shaft ground brush		Only if in combination with motor shaft ground brush or insulated coupling	X	X	May cause increased motor bearing current without motor shaft ground brush, faraday shield or insulated motor bearings

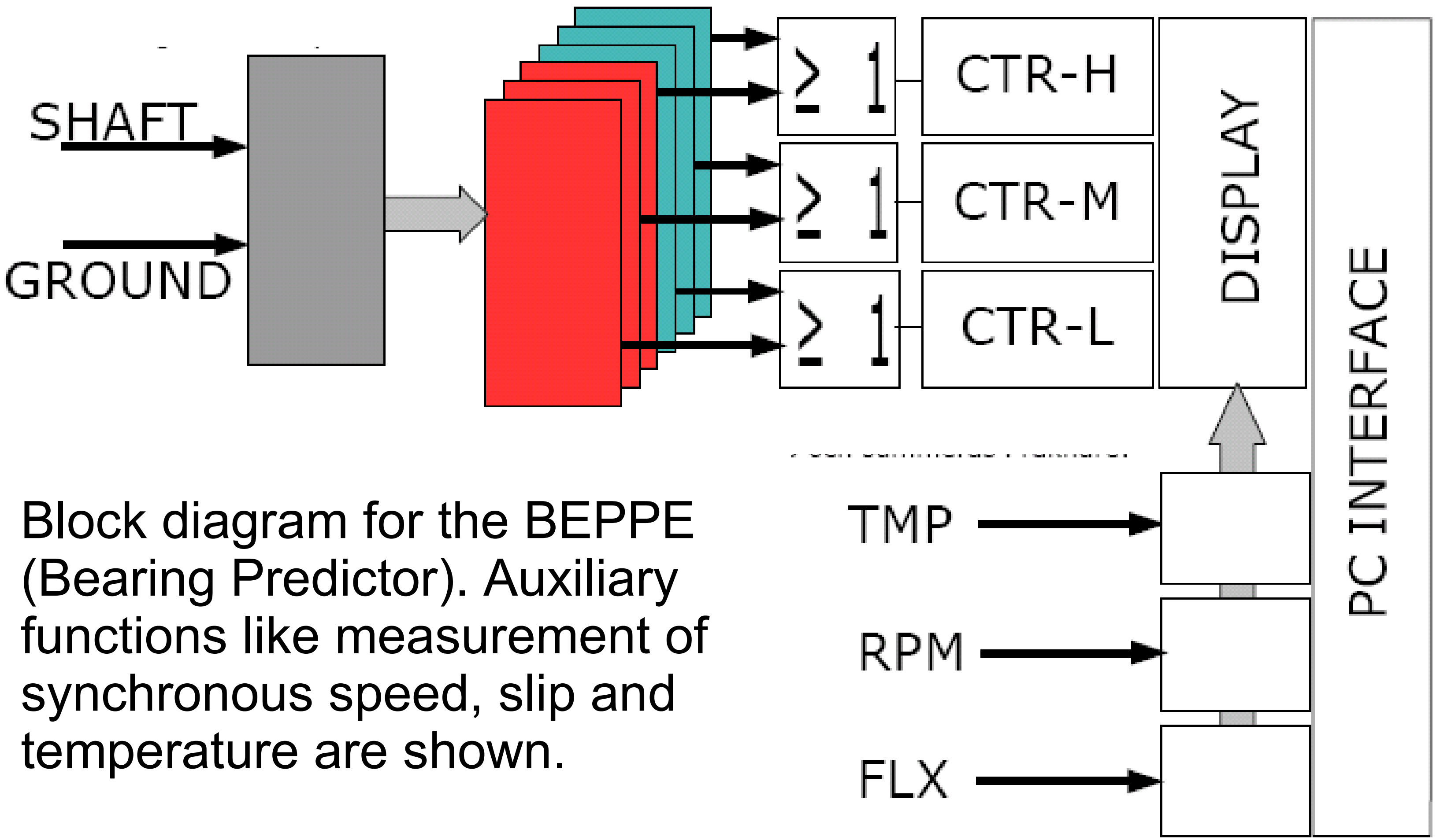
EDM Signature

The shaft voltage is an often chaotic misch-masch of signal components. The EDM discharge stands out in one way – it is the only signal that has a rate-of-change more than 50-100 MV/s and that ”lands” at zero (or close to) volts.



The charging phase looks differently, depending on what the energy source is. But the discharge is always the same – a steep voltage drop going to 0 V. This is the property used to find and discriminate EDM.

EDM Signature and Measurement



Block diagram for the BEPPE (Bearing Predictor). Auxiliary functions like measurement of synchronous speed, slip and temperature are shown.

EDM Signature and Measurement

There are several prototype implementations of the Bearing Predictor. The display of an early unit is shown.

PPS = Pulses Per Second

H = 200 MV/s
M = 100 MV/s
L = 50 MV/s

EDM Signature and Measurement

Another version contains discriminator and counters in a separate unit that communicates with a PC via Hyperterminal or other asynchronous protocol. A printout example is shown below. Sorry, Swedish, but hopefully understandable.

```
. DATUM, OPERATÖR:  2006-11-03/ENGLUND

. MASKIN, POSITION: PUMP B
. KOMMENTARER:      I DRIFT

. MÄTNING NR: 7

---------------------------------------------
. ANTAL GENOMSLAG VID 200 V/us:  0 PPS

. ANTAL GENOMSLAG VID 100 V/us:  91 PPS

. ANTAL GENOMSLAG VID 50 V/us:   8683 PPS
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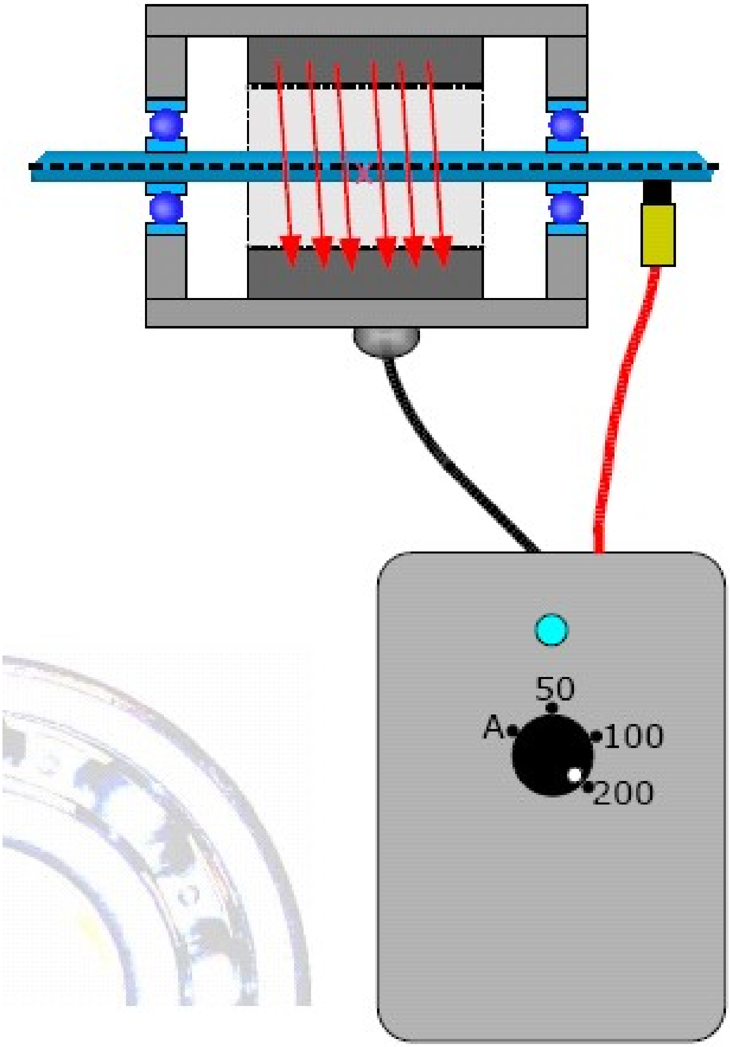
EDM Signature and Measurement



There is also the ”Lill-Beppe”. A hand-held battery-driven unit that can be used to detect EDM activity in bearings. A magnet connects to ground and a carbon electrode is used to contact the shaft. V/µs (MV/s) is set with the knob and when there's no activity (LED blinks when there is EDM) at levels at or above 100 MV/s, there is no risk that EDM will shorten the bearing's life.