

# ROTATING MACHINES - PROS AND CONS OF MONITORING DEVICES

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**Abstract** – Rotating machines such as motors, generators, turbines, and compressors utilize many different types of monitoring devices. These devices are critical for the long term reliable operation of rotating machines.

Some measuring devices will add significant knowledge of the performance and therefore add value and reliability, while others add little to no value but will add substantial cost. The pros and cons of using each of the many different types of devices and what can be determined from the measurement need to be evaluated before installation. Simply installing the device may not add the expected reliability. This paper will discuss parameters of monitoring, setting of control limits, and the application of various monitoring devices.

*Index Terms* — Rotating machine, motors, generators, monitoring, vibration, temperature, alarm, trip

## I. INTRODUCTION

Induction motors are the most popular type of prime mover for rotating equipment because they are highly reliable, have good efficiency, and are simple. Although this paper focuses on induction motors, it is also applicable to generators and synchronous machines. There are many factors that cause motors to fail. For long-term reliability and good performance, these failure factors should be understood, monitored, and maintained. It is important to understand the benefits of proper motor protection and the risks if the motor is not properly protected. Various components of induction motor performance can be monitored. Some monitoring devices are critical for ensuring proper motor performance, while others may be of little value and add only unnecessary costs. Large machine as defined by NEMA MG -1 PART 20 or critical machines where machine is a prime mover and its failure will cause loss of the revenue and downtime may warrant greater protection. In these cases, the benefits could far outweigh the costs.

The first task is to decide what needs to be monitored. The second task is to select appropriate machine protection devices, identify proper settings, and take action based on the monitored results. Induction motors have certain absolute limits that must be monitored and controlled. In most cases, these upper end limits are blindly used. If this practice is applied on motors that normally run considerably better when not applying the preset limits, considerable changes in the motor performance can occur before an alarm is triggered; therefore it is critical to establish the proper settings for the alarm and trip. If relays are set too high, problems could go undetected. If set too low, it could lead to nuisance trips. Many times it is better to

trend the performance for a period of time before establishing the final settings. This implies that trending offers the most protection. An additional consideration when selecting alarm settings is that changes in the performance of the driven load can also affect the motor's overall performance. In this paper, any references to motor or machine will refer to the motor driver, while any references to the load machine will refer to the driven load.

## II. PARAMETERS OF MONITORING

The critical components of an induction motor that need to be monitored include:

- A. *Voltage and current,*
- B. *Stator winding insulation integrity,*
- C. *Vibration of the bearings and motor enclosure,*
- D. *Temperature of the winding, bearings, and cooling media,*
- E. *Speed,*
- F. *Pressure of the cooling media, and*
- G. *Flow of the cooling media.*

The above list of parameters is by no means a complete list; any other parameters to be measured will depend on the end user. The monitoring methods and degree of protection can vary significantly.

## III. MONITORING CONSIDERATIONS

### A. *Voltage and Current*

Voltage and current are key performance characteristics of an induction motor. Voltage will not normally change over time and may not be monitored. Concerned with voltage fluctuation is shown in table II. Current could vary based on loading conditions, and these could change for many reasons. As a result, current should be monitored live on critical applications, particularly where the load may change.

Motor voltage can be measured between the stator phases or between a phase and ground. A high-voltage terminal box, as shown in Fig. 1(a), makes it easier to visualize the 3 phases. A ground wire and pad can be seen in the back on the right side. Many motors have three or more leads hanging out of the motor, as shown in Fig. 1(b). These leads may be labeled only and not be tied to any terminal block or accessories. The determination of which phases are A, B, and C and need to be tied to L1, L2, and L3 can be determined only by lead tagging. National Electrical Manufacturers Association Motor and Generator section 1 (NEMA MG1) part 4 [3] establishes the tagging identification as T1, T2, and T3, etc., but the direction of

rotation is not defined for most types of motors. Therefore, connection diagram documentation from the manufacturer is required. At times, U, V, W etc. may be used per IEC standard IEC 60034-8 [7]. This IEC standard establishes the direction of rotation. In more complex connections, a connection plate may be required.

Voltage measurements can be taken between the posts of the lightning arrestors (LAs) shown in the front-bottom of the box in Fig. 1(a). If the voltage measurement is measured too far from the motor, the voltage drop to the motor could give incorrect readings. The motor terminals may be connected to the same post or to the surge capacitor (SC), shown behind the LAs. Many types of meters can be used to measure voltage. What voltage to measure or the accuracy and resolution required will depend on the concern that needs to be addressed. Table I identifies some critical measurements that should be taken, depending on what kind of problems or concerns exist.

The first questions would be: why do you want to measure this in the field? What can be learned? If the concern is with voltage sag, then a phase-to-phase (Ph-Ph) root mean square (RMS) voltage measurement may be all that is required. Normally, voltage is measured only at commissioning or when there is an operational concern that needs to be addressed, but some type of over or under-voltage monitoring may be considered if the power supply to the motor is not solidly grounded. If the motor is running on a variable frequency drive, and a turn-to-turn failure is a concern, then the rate of rise of voltage (dv/dt) of the incoming voltage wave should be measured with an oscilloscope and HV probe. Optional investigative measurements and their reasons are described in Table I.

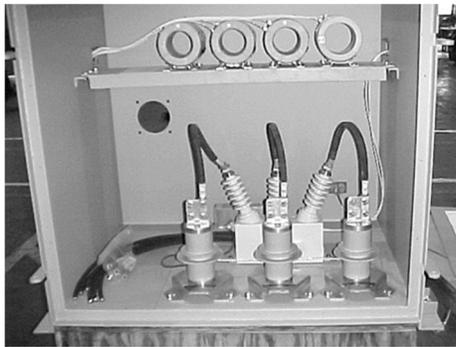


Fig. 1 (a) Three Phase Connection



Fig. 1 (b) Motor Leads

TABLE I  
INVESTIGATIVE VOLTAGE MEASUREMENTS FOR  
TROUBLESHOOTING

Observed Problem or Failure *	V <sub>PH-PH</sub> RMS	V <sub>Ph-G</sub> RMS	V <sub>Ph-Ph</sub> Peak	V <sub>P-G</sub> Peak	dv/dt	V <sub>N-G</sub> Peak	V <sub>S-G</sub> Peak
Motor Won't start or takes too long	X						
Stator Ph-Ph*	X		X				
Stator Ph-G*		X		X			
Stator T-T*			X	X	X		
Bearing Shaft Current						X	X

Note:  
 Ph-Ph = Phase to Phase  
 Ph-G = Phase to Ground  
 N-G = Neutral to Ground  
 S - G = Shaft to Ground  
 dv/dt = Rate of change of voltage with respect to change in time

TABLE II  
MONITORING OF VOLTAGE CURRENT & PD

Monitor	Weak Power systems	Ungrounded systems	Critical Applications	API 541 Rec,
V <sub>PH-PH</sub> RMS	Consider	Not Necessary	Consider	Rarely Used
V <sub>Ph-G</sub> RMS	Not Necessary	Consider Overvoltage Relay or monitoring	Not Necessary	Rarely Used
I <sub>Ph = Phase Current</sub>	Not Rec.	Not Rec.	Recommended (Rec.)	When requested Usually Window Type
Partial Discharge			X	Optional requirement. >4160V

Note:  
 RMS = Root Mean Square  
 Ph-Ph = Phase to Phase  
 Ph-G = Phase to Ground  
 PD = Partial Discharge

The effects of a motor running under-voltage or over-voltage are as follows:

**UNDER-VOLTAGE (down to ≥ 10%)**

- Motor runs slower

- Motor requires greater current to produce rated power output
- Motor normally runs hotter at rated output
- At rated current, motor could produce on  $\geq 90\%$  rated power out (may run cooler if not over saturated)
- Motor has lower starting torque  $\approx$  Voltage<sup>2</sup>
- Greater losses which lowers the efficiency

**OVER VOLTAGE (up to  $\leq 10\%$ )**

- At rated current, power output may be up to 110% of Rated power (may not be a negative)
- Motor has greater core loss (may run hot)
- Lower current setting
- Higher voltage stress shortens insulation life

In North America, most motors are expected to conform to NEMA MG -1 [3], and it states that motors must be capable of starting and running at  $\pm 10\%$  of rated voltage. However, it is acknowledged that the performance may change. The motor may run hot or have some of the other performance deviations, as listed above. Beyond  $\pm 10\%$ , there is no guarantee that the motor will perform, start, or run unless a custom motor is specifically designed for the application. It is highly recommended that during commissioning, the motor voltage is measured Ph-Ph and phase-to-ground (Ph-G), and that corrections are made if the voltage is out of specification. Insulation systems life expectancy is based on rated voltage. Manufacturers can predict the reduction in insulation life based on over-voltage. Reduction in life would be slight if the level and magnitude are small all the way to instantaneous if the level is high. Note that the rated phase-to-ground voltage plus 10% over-voltage allowance is

$$V_{ph-G} = V_{ph-ph} / \sqrt{3} \pm 10\%.$$

Where

$V_{ph-G}$                    Phase to ground voltage  
 $V_{ph-ph}$                    Phase to Phase voltage

If voltage quality and voltage spikes are of concern, it may be necessary to measure voltage using a high-resolution oscilloscope to determine the peak instantaneous voltage and dv/dt phase to phase (Ph-Ph) as well as phase-to-ground (Ph-G). With this plot, one can also see if there is a neutral shift to ground (G-N) of the incoming voltage, which can cause shaft currents and failure. [11] [12]

In most applications, voltage monitoring is not continuous because it is normally under control once commissioned. But when a problem occurs, such as when the motor does not start or a stator or bearing failure occurs, voltage measurement would be one of the first diagnostic steps. Which voltage should be measured? Fig. 2 shows the shift in neutral and its effect.

The current may be measured as described by the Current Transformers (CTs). When the box contains four CTs, as shown in Fig. 1(a), three of the CT's are typically used for self-balancing differential or zone differential protection to protect the system against Ph-Ph or Ph-G faults, thereby taking the motor off-line within 2 to 3 cycles of AC supply to minimize damage. Normally, when there is a fourth CT, it is used to monitor current. Current transformers are used to provide currents of reduced value, which are proportional to the currents to be measured. Current monitoring in one phase is

normally adequate because all three phase currents must add to zero, and the phase angle between the three phases of 120 degrees is normally not a concern.

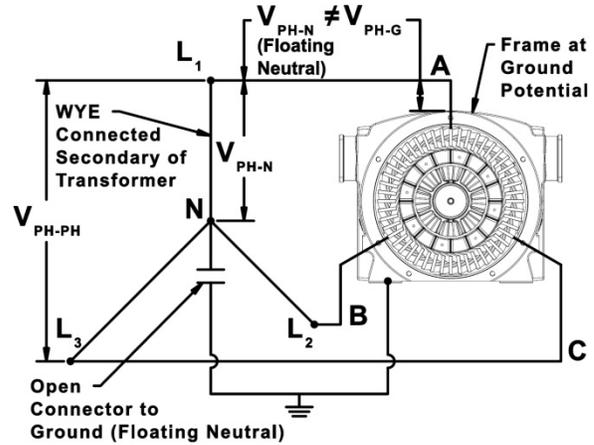


Fig. 2 Shift in neutral voltage

By measuring the RMS phase current, the load can be estimated. The current is high, because either the voltage is low or the load is excessive. Current higher than the rated current will normally cause overheating, which will shorten the insulation life or lead to rapid failure, depending on the magnitude of the current. The use of a service factor adds some confusion. The current demand at 1.15 service factor may not be part of a standard data sheet, and the operator may set the limit at 1.15 times the rated full load current. This could at times cause the motor to run hot because it was designed to meet the design temperature at 1.15 times rated load, which may not correspond to 1.15 times rated current. This needs to be confirmed with the motor manufacturer. It is recommended that an alarm be triggered any time the design current is exceeded. It is important to note that current transformers are non-sparking devices and can be installed in hazardous locations where the hazardous gases present occasionally such as division 2 area as defined by NEC or UL standard.

Measurement of voltage and current are self-explanatory. Care should be taken when measuring the voltage of adjustable frequency drives (ASDs). A true RMS meter is required to measure the RMS value. See Table II for monitoring recommendations (Rec.).

**B. Insulation Integrity Measurement**

Typically, the integrity of the stator winding insulation is measured off-line and on line. Off-line tests that may be performed include Meg-ohm measurements, high potential tests (Hi Pots), surge tests, and partial discharge tests. High potential and surge tests are not used for continuous monitoring

1) *Meg-Ohm Test*: The meg-ohm test is not a monitoring test; mostly it is performed at planned maintenance. It measures the resistance in the winding insulation between the winding and the motor frame. This test is the least damaging to the insulation and should be performed before any other insulation tests are performed or before the motor is put into service. The polarization index (PI) test is a meg-ohm test

performed over ten minutes in accordance with IEEE 43 [8] and can determine the appropriate cleanliness or moisture in the insulation system. It is not a test that is used for continuous monitoring of the insulation. With these tests, it may be possible to make repairs to the system before damage occurs.

Measurements should be taken at  $25^{\circ}\text{C} \pm 15^{\circ}\text{C}$ . The maximum insulation resistance of the winding to ground is measured at 500-10,000 VDC depending on the rated voltage per IEEE 43 [8]. A meg-ohm meter used for these measurements is shown in Fig. 3. It is similar to a multi-meter when the latter is in its ohm meter function; however, its output voltage is *much higher* than that of a multi-meter.



Fig. 3 Meg-ohm Meter

2) *Surge Test*: A surge test is also not a monitoring test. This test is normally performed during a maintenance cycle or when a problem occurs since it can be destructive.

3) *High Potential Test*: A Hi Pot test is a destructive test and must not be performed repeatedly. It is sometimes questioned whether it should be performed at all because a failure would require a complete rewind of the stator. In critical applications, it may be necessary to perform this test if there is time to repair and ensure the future reliability of the process. This test is sometimes performed using DC voltage ramped up slowly in steps. The leakage current is plotted, and then the test is stopped before damage occurs. In general, the DC test is less destructive than an AC Hi Pot test. When performing either test in the field, the test should be conducted at only 60-65% of the new motor's high-pot voltage, per IEEE 43.[8]

4) *Partial Discharge Test*: Historically, partial discharge (PD) testing has been performed off-line. In recent years, considerable work has been done to establish testing procedures and equipment for on-line testing.

When electrical sparks develop across voids in a high-voltage winding, PD occurs. Thermal aging, abrasion, and mechanical forces can lead to insulation delamination and voids. Contamination or damage to the conductive or partially-conductive surface can contribute to PD. All these symptoms are signs of a degrading insulation system. The number of these electrical sparks and discharges can be measured, and is an indication of the number of voids in the insulation. Degradation of high-voltage insulation can be established well in advance of a failure. The higher the system voltage, the greater the advance notices for a failure. Testing for PD could give 2 to 5 years' advance notices for a 6 kV or higher voltage machines or several weeks' notice for 2.3 kV or 4 kV machines.

On-line or in-operation PD testing is one of the few available tests to continuously monitor stator winding integrity. All other methods are normally performed off-line. This test requires that the machine must be equipped with capacitors on the motor terminals, and this may require an oversized terminal box. These capacitors will provide a capacitive coupling, which allows high-frequency discharges to be passed through and be monitored.

It remains controversial as to whether absolute PD values can be used to determine insulation integrity. The danger in setting an absolute limit is that if it is too conservative, it may result in a good machine being taken out of service or unnecessarily refurbished. It is still believed by many that this test should be used for trending over time until enough tests are conducted to establish levels. The latest standard that discusses this for off-line testing is IEC 60034-27-1 [1], which went out for ballot in late 2015. IEC 60034-27-2 [2] covers on line testing. To identify which machines require attention, two quantities need to be monitored over a period of time: the peak partial discharge magnitude,  $Q_m$ , and the total partial discharge activity (NQN). While  $Q_m$  is defined as the magnitude corresponding to a repetition rate of 10 pulses per second, NQN measures the severity of deterioration in the worst location of the winding. The former is a scalar quantity and is more indicative of how close a winding is to failure.

### C. Vibration Monitoring

Vibration monitoring provides an overall indication of the progression of the machine's health. Also, vibration trends are widely used as a predictive maintenance tool.

Vibration is measured on the motor housing and/or rotor shaft, depending on motor design. In motors with anti-friction bearings, the supporting bearing housing follows the rotor motion because the bearing stiffness is greater. In these cases, measuring the vibration on the bearing housing is sufficient and will also indicate rotor motion. However, in motors with a sleeve bearing design, the rotor is softly supported, and the housing does not closely follow rotor motion. In these designs, measuring the rotor motion is critical because the rotor motion can be significant, while the bearing housing motion is not. The rotor and bearing housing vibration is commonly monitored in motors with the sleeve bearing design (see Table III).

Vibration can be measured in displacement, velocity, or acceleration units. Housing vibration measurements are widely made using velocity because it is directly related to machine fatigue and its kinetic energy. The velocity unit is also widely used in vibration diagnostics and is the unit of choice for most vibration specifications for seismic measurements of motor housings (for example API 541 [4]). Acceleration units may also be used for housing vibration measurements if there is interest in monitoring vibration at higher frequencies.

Rotor vibration is normally measured in displacement units and in vibration signal peak-to-peak values, which are usually expressed in mils (0.001 of an inch) or micro-meters.

The location of the measurement sensor is also important. Housing vibration is measured using accelerometers, as shown in Fig. 4, placed as closely as possible to each bearing in the horizontal, lateral, and vertical directions.

TABLE III  
MEASUREMENT LOCATIONS FOR VARIOUS MOTOR  
DESIGNS

Measured Location	Motors with anti-friction bearings	Motors with sleeve bearings	API 541
Accelerometers, Seismic sensors for Bearing Housing	Important	Useful	Opt. on AF Bearing. Opt. Sleeve Bearing. ≤ 1200 RPM
Radial Rotor shaft Proximeter. Probes	Not useful	Important	Opt. for ≥1200 RPM
Axial Proximeter. Probe for Hydro. Thrust Bearing.	Useful	Useful	Provision Required Prob. Opt.
Vibration Switch	Useful	Useful	Not Rec. Seismic or Prox. Probes Preferred

Note:  
Opt. = Optional  
Rec = Recommended  
RPM = Revolution per minute  
Prox. = Proximeter

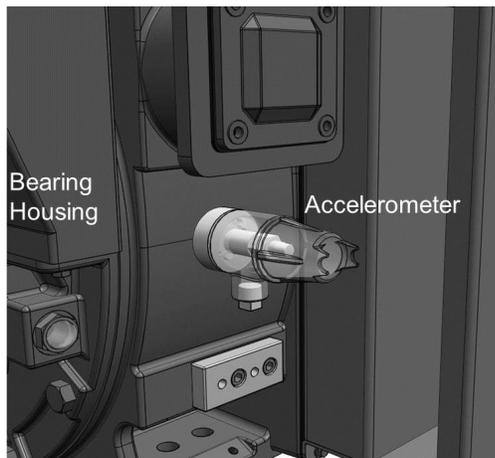


Fig.4 Accelerometer Located Close to Bearings

An accelerometer is an electromechanical device that will generate an electrical signal proportional to the movement in the machinery where it is attached. There are many types of accelerometers. Some accelerometers use the piezoelectric effect, while others sense the changes in capacitance with some circuitry to convert from capacitance to voltage.

There are other housing vibration measuring devices such as the seismometer, which directly measures velocity. It is highly sensitive, but large in size and has frequency range limitations. It is simply a seismic mass supported by a spring, and it moves in a permanent magnetic coil. It is different from a velometer, which is a specialized piezoelectric accelerometer that incorporates embedded integrated electronics in a solid-state design. Accelerometers have no moving parts, do not suffer from mechanical degradation and wear, and can be mounted vertically, horizontally, or at any other angle of orientation. Additional methods include the use of piezo-resistive effect, hot air bubbles, or light.

Motor shaft motion is measured using eddy current probes. An eddy-current proximeter (prox.) probe works by passing an alternating current through a coil of wire and measuring the coil's impedance. This impedance changes when the probe is brought near an electrically-conductive material. The impedance change is proportional to the physical gap between the coil and the conductive target. The sensing module in turn converts this impedance change to a voltage, providing an electrical output directly proportional to the physical gap. Eddy current probes are shown in Figs. 5(a) as installed in machine and 5(b) as a standalone.

Applying eddy-current transducers requires careful attention to detail. The following factors should be considered while installing, calibrating, and monitoring:

- Target material
- Target geometry
- System length (total cabling)
- Mounting considerations (e.g., counterbore, bracket resonances, and installation convenience)
- Environment (e.g., temperature, chemicals, and radiation)
- Frequency response
- Linear range
- Signal-to-noise ratio (e.g., device resolution and electrical runout)
- Field wiring

Capacitive proximity sensors are similar to inductive proximity sensors. The main difference between the two is that capacitive proximity sensors produce an electrostatic field instead of an electromagnetic field. Capacitive proximity switches will sense metal as well as nonmetallic materials such as paper, glass, liquids, and cloth.

The sensing surface of a capacitive sensor is formed by two concentrically-shaped metal electrodes of an unwound capacitor. When an object near the sensing surface, it enters the electrostatic field of the electrodes and changes the capacitance in an oscillator circuit.

Monitoring vibration should consider setting limits for alarm and shut down. A value of 200% to 300% of the housing vibration limit of a new motor can be used to set such limits. For example, a vibration specification limit of 0.1 ips (2.5 mm/sec) will yield an alarm at 0.2 ips (5.8 mm/sec). This limit may be lowered or raised where a special limit should be set. For example, it can be raised if the motor is mounted on a flexible base and exists in a significant vibration environment. A lower limit may result in nuisance alarms and trips. On the other hand, a slow motor on a steady massive base will normally run at a very low vibration level, and the limits may be lowered. A common example is a slow running motor that has a vibration

level less than 0.04 ips and has a new motor specification limit of 0.1 ips with an alarm limit of 0.2 ips. The motor vibration would need to increase 5 times before the alarm is activated, which may be too late to prevent failure. In these special cases, an alarm of 0.1 ips and a trip of 0.15 ips may be more appropriate.

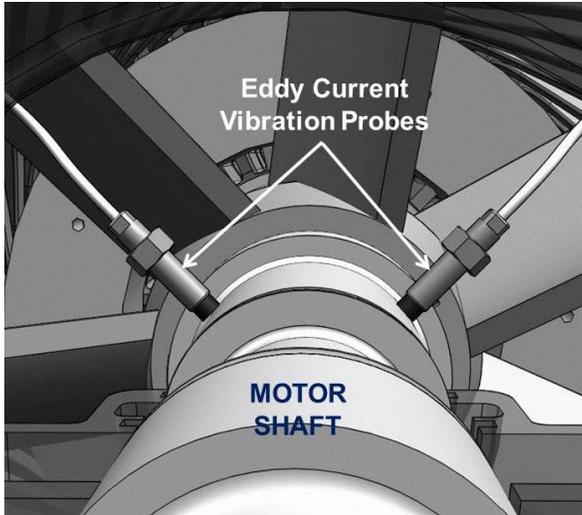


Fig. 5 (a) Eddy Current Vibration Probe



Fig. 5 (b) Eddy Current Probes

D. Temperature Measuring Devices

1) *Stator Measurement:* The stator is one of the most expensive and critical components of an induction motor. The stator needs to be protected against over-voltage and over temperature. The voltage and current component should be considered as previously discussed. It is highly recommended that the temperature in large machines in critical applications be monitored on a continuous basis, utilizing resistance temperature detectors (RTDs), as shown in Fig. 6.

Using generic maximum alarm and shutdown temperatures may or may not protect the motor against overheating and failure, and also may not provide advance notice of potential faults unless the temperature and its trends are continuously monitored and watched, taking action when the trend goes in the wrong direction. It is also possible that overheating in an isolated location could occur with only a minor change in the hot spot temperature where the RTD is located. Most manufactures will provide maximum alarm and shutdown temperatures for the RTD's, but many machines run at partial loads. For example, a class F insulation with limits may have a recommended alarm temperature of 155°C and a shutdown temperature of 170°C. Because of the manufacturer's conservatism and the end user's added margin on the load to ensure added reliability. It is not unusual for the actual load in the field to range between 50% and 75% of the rated load. As a result, a class B rise motor with class F insulation, which is typically required per API 541, may experience a 20-45°C rise over a 40°C ambient temperature at load. The maximum ambient temperature may be even lower than the standard 40°C at the 25-40°C rise. As a result, the actual temperature level measured in the field could be as low as 45°C (25+20) or as high as 85°C (40+45). Severe damage can occur before the stator reaches 155°C. If monitored and trended properly, there would be plenty of advance notice.



Fig. 6 Location of Temperature Detection Devices in Stator Slots

Consider a double-end-to-center ventilated machine as shown in Fig. 7 if the rotor vents became clogged by dirt, the RTD located in the core could pick up the temperature increase quickly. But if the coil ends were blocked, the temperature of the end windings can increase significantly while only a minimal change is sensed in the RTD. The same would be true for the single-end ventilation air flow design shown in Fig. 8

On smaller, less critical machines, devices such as thermostats and thermistors can be installed in the end windings. However, they are not monitored and will not give an early indication of potential failure. Smaller machines may be a stock product and easily replaced, but if the process is critical, continuous monitoring is recommended. On random-wound

low-voltage machines, it may be difficult to get the RTD stick into the slot, so small thermocouples could be considered so that trending would be possible.

Totally-enclosed fan-cooled (TEFC) machines generally have a more even distribution of heat and may not be as sensitive to abnormal deviations in air flow and cooling. On TEFC, motors most of the heat exits the motor through the fins that are close to the stator core area. The heat dissipates through the air blowing across the fins. These machines tend to run hotter on the end windings because the heat primarily leaves the motor through the core area.

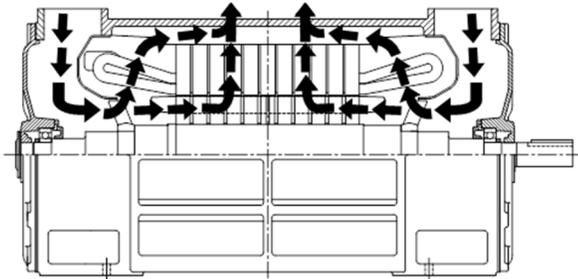


Fig. 7 Air Flow Pattern, Double End to Center Ventilation

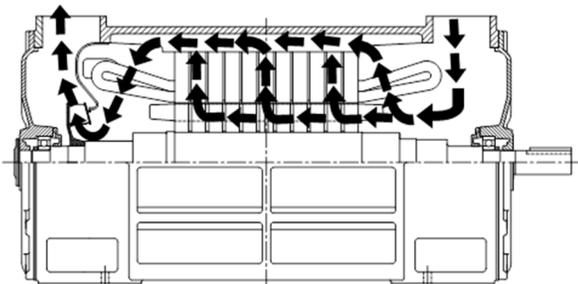


Fig. 8 Air Flow Pattern, Double End to End Ventilation

A TEFC machine may have a much smaller difference in temperature along the length of the coil, so that the location of the temperature-measuring device may be much less significant. However, the location of the device may depend on the size of the machine, winding type, or how critical the application is. Some larger machines will introduce internal air circulation to evenly distribute the heat.

It is interesting to compare the internal winding temperatures, as shown in Fig. 9 on various types of ventilation schemes. The difference between the end winding temperature and the core winding temperature could be 30°C or more on an open machine, whereas in a TEFC, it could easily be within 10°C.

On high-voltage machines above 10 KV, the end winding may run significantly hotter because of heavy insulation on the end. Though the surface of the coil is cool, the copper inside the coil can run much hotter.

These variations make it clear that trending temperature over time and setting alarm levels much closer to the operating temperature may be a better solution. For example, setting the alarm at 10°C degrees above the operating temperature would

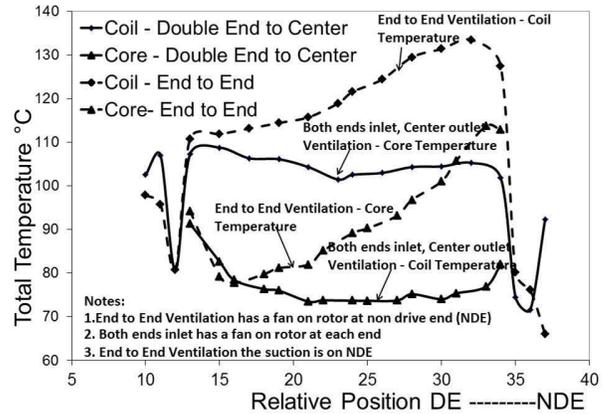


Fig. 9 Core and winding total temperatures versus ventilation type

allow the operator time to check the motor and determine why the temperature is rising. If the alarm was set at 55°C and then it was determined that the ambient temperature rose by 15°C, the alarm could then be set to 60°C, and the operation could continue with confidence.

2) *Bearing Measurement:* Two primary ways of protecting motor bearings are through temperature and vibration detection. Both methods of protection are equally important for sleeve and anti-friction bearings. The same concerns apply to monitoring bearing temperatures as they do for stators. Sleeve bearings can run extremely cool, where significant changes in bearing temperatures do not trip an alarm. In some cases, a sleeve bearing can actually wipe around the Babbitt area, and the temperature may rise only 10°C. The alarm may not trip, and the need for repair would go unnoticed until the bearing completely fails. It is better to schedule the down time.

3) *Resistance Temperature Detectors:* Resistance temperature detectors are used in conjunction with an RTD controller to monitor and control the motor. Some stick type RTDs are shown in Figs. 10(a) and 10(b). The RTD resistance varies with the change in temperature, which is fed to a signal conditioner that adjusts power to the thermal system. Depending on the criticality of the application, various types of probes with various capabilities may be used. The merit of each one is shown in Table IV.

4) *Thermistors:* Thermistors work in conjunction with a control module set to trigger a motor alarm or shutdown when the temperature and resistance meet defined levels. Normally, the thermistors and the control module cannot be mixed but instead must be purchased as a set. Thermistors, as shown in Fig. 11, come in many sizes and can be as small as 0.020 inches.

Positive temperature coefficient (PTC) thermistors can be used to limit temperature, but are not used for trending. They would not be recommended for large critical machines where machine is a prime mover and its failure will cause loss of the revenue and downtime. Thermistors can be slow to respond to rapid temperature changes because they are mounted on the surface or embedded in the end winding. This makes them less effective for transient changes such as when starting or a

Table IV  
Temperature Measurement Device

	Thermistor	Thermostat	Thermometer	RTD	Thermocouple	API 541
Used on Small Motors Random Wound Motors	Recommended (Rec.)	Rec.	Not Rec.	Not Rec.	Opt.	N/A
Used on Large Form wound motors	Not Rec.	Opt.	Not Rec.	Rec. (API)	Opt.	Rec. 100Ω Din Preferred
Used on Stators	Yes	Yes	Not Rec.	Rec. (API)	Opt.	Rec. 100Ω Din
Used On Bearings	No	Yes	Not Rec.	Rec. (API)	Opt.	Rec. 100Ω Din
Air In & Air Out of H <sub>2</sub> O Cooler	No	No	Yes	Rec.	Opt.	Rec. & Req.
Response to stator temperature change	Medium	Slow	Slow	Fast	Fast	Info
Advance Notice of Failure	Only if second set for Alarm	Only if second set for Alarm	Yes But slow	Yes	Yes	Info
Requires separate control Module	Yes	No	No (Built In)	Yes	Yes	Info
Used for Trending	No	No	Possible	Yes	Yes	Info
Trending Limit	NA	NA	20% Over Normal Temperature			Info
Alarm Limit for class F Insulation	Per manufacturer	Per manufacturer	Per manufacturer	Stator 145-155°C	Stator 145-155°	Info
Alarm Limit	Per manufacturer	Per manufacturer	Per manufacturer	Bearing 80-90°C	Bearing 80-90°C	
Trip Limit For Class F Insulation	Per manufacturer	Per manufacturer	Per manufacturer	Stator 155-170°C	Stator 155-170°C	Info
Trip Limit	Per manufacturer	Per manufacturer	Per manufacturer	Bearing 90-100°C	Bearing 90-100°C	
Cost	High	Low	Moderate	High	High	Info

stalled condition is reached. These devices may be wrapped in a foil to improve heat transfer. They are smaller than a thermostat but respond much faster. Thermistors are recommended over thermostats on smaller machines where rapid heating conditions, such as a stalled condition, are more

likely. For added precautions against shorts in the probes, the controller will also trip the motor off-line if the resistance is too low. Thermistors are not used on bearings.

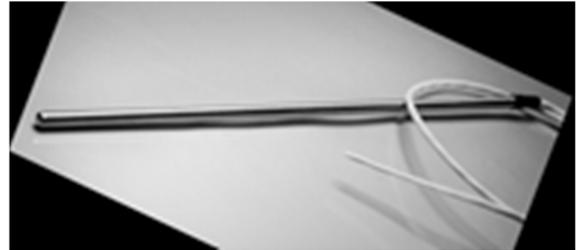


Fig. 10 (a) Resistance temperature detector (RTD) Devices in Well

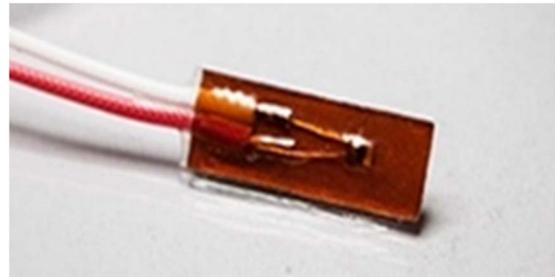


Fig. 10 (b) Resistance temperature detector (RTD) an open construction

In general, a thermistor will maintain a low resistance and then increase resistance rapidly with a minimal change in temperature. Two or more sets of probes can be used, each of which have different temperatures versus resistance characteristics so that they will alarm or shutdown at different temperatures. The matched control module can be sourced with one or two or more sets of probes with temperature versus resistance characteristics that can trigger an alarm or trip the motor off-line at different temperatures. In general, thermistors should not be used for monitoring, as thermistor needs a separate thermistor relay which may introduce the delay in triggering alarm or trip condition.

The controller may have a single pole double throw (SPDT) switch that will open a set of contacts that may run to the holding coil of the starter, opening the circuit and shutting down the motor. The other contacts may be connected to trigger an alarm. The control module could also have a second set of contacts, referred to as double pole double throw (DPDT) switch. A second set of thermistors, designed to transition at a different temperature than the first set, can be installed on the stator winding. This allows the alarm and shutdown to occur at different temperatures.

Negative temperature coefficient (NTC) thermistors are not commonly used, but can be used to monitor temperature. Typically, RTD's or thermocouples are selected if temperature monitoring or trending is required.



Fig. 11 Thermistor

5) *Thermocouples*: Thermocouples are constructed of two dissimilar metals that are welded together. When the temperature changes, a milli-volt signal is generated that is fed to an instrument which amplifies the signal and uses it to control the system. Thermocouples are available in various wire sizes down to 30 AWG. Two major types are used: the open ended type or the type encased in a steel tube, designed for harsh environments. Examples are shown in Figs. 12(a) and 12(b).

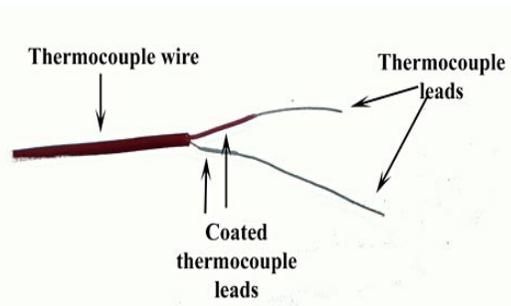


Fig. 12 (a) Open Thermocouple



Fig. 12 (b) Thermocouple probe in housing

6) *Thermostats*: Two basic types of thermostats are used. One is a snap-action and the other is a slow make break (SMB). A snap-action thermostat opens contacts using a bi-metal disk that snaps when the opening temperature is reached. The snap-action quickly opens and separates the contacts. The contacts will not re-set until the bi-metal disk reaches the re-set temperature, which is called the differential. With a snap-action thermostat,

accuracy is, at best,  $\pm 10^\circ\text{F}$  differential. This is also called the hysteresis in the bi-metal. The advantage is a long life, ability to handle resistive, inductive, and DC loads, high amperage, and the ability to act as a high limit switch. Snap-action thermostats can also offer manual reset features.



Fig. 13 Bi-metallic Thermostat

An SMB switch operates by slowly pulling the contacts apart a short distance at the opening point and then resetting when the differential is reached, usually  $2\text{-}5^\circ\text{F}$ . This type of switch offers close temperature control, but because the thermostat opens and closes often, it does not have the life of a snap-action thermostat. These thermostats are small and sometimes have an electrically live case. As a result, they are insulated, typically with molded silicone or butyl insulation. They handle only AC resistive loads, and because of their size and method of mounting on stators, they are slow to respond to rapid changes and cannot be used for trending. They are often used in safety-related environments because no other intermediate controller which could fail is required to trip the motor off-line. They can be connected directly to the holding coil of a starter and trip the breaker when the circuit opens. Fig. 13 shows a bi-metallic type thermostat.

E. *Speed Measuring Devices*



Fig. 14 (a) Electronic Tachometer



Fig. 14 (b) Strobe type Tachometer

Measuring rotational speed is important for an induction motor or generator. Rotational speed measurements can be used to check the machine performance and output power,

and it also can complement trend analysis and machine diagnostics. Various types of measuring devices are available.. An electric tachometer is shown in Fig. 14(a), while a strobe type is shown in Fig. 14(b).

A stroboscope, also known as a strobe, is an instrument used to visually "freeze" a rotating rotor by shining a light that alternates at a frequency equal to the rotor speed, making the rotor appear stationary.

Electric tachometers operate on the principle of counting the number of revolutions during some period of time, but the number of revolutions is measured in an optical way. This is more suitable for continuous speed monitoring. There is no specific limit on motor speed variation, but there are limits on the maximum frequency variation from the power supply, which will be proportional to speed, and that may carry a time limit. A  $\pm 5\%$  limit is established on the frequency by NEMA MG 1, [3] and some controllers will require a steady signal for certain time to process by the controller on the frequency variation, depending on the loading condition.

**F. Pressure Measuring Devices**

There are a variety of instruments used to measure absolute or gauge pressure. Pressure measurement devices can be separated into two categories: mechanical and electronic. In the mechanical type, the height of the liquid in a manometer is directly proportional to the hydrostatic pressure. There are three major sub-types: differential, sealed ends, and open ends. In the differential type, the two ends are exposed to different points along the flow path. In the sealed end manometer, one end is open to the fluid of interest, while the closed end encloses a vacuum. In the open-end manometer, one arm is exposed to the fluid being monitored, and the other open to the atmosphere. Various types of pressure measuring devices are shown in Figs. 15(a to d)

Among electronic devices, there are several sub-types:

- Manometer – Fig. 15(a and b)
- Strain gauge– Fig. 15(c)
- Capacitance– Fig. 15(d)
- Potentiometer
- Piezoelectric Elements
- Linear Variable Differential Transformers (LVDTs)

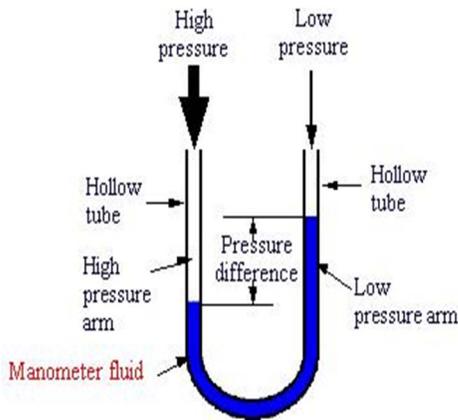


Fig. 15 (a) Mano Manometers



Fig. 15 (b) Mano Manometers as Installed

Pressure instruments are used to monitor the cooling air pressure drop inside the motor, which is an indication of how clean or obstructed the air passages may be (mainly at the intake air filter). They are used for measurement of the pressure drop or as a switch that will issue an alarm or shut down the motor when acceptable limits are exceeded. The limits depend on the motor size, enclosure size, motor type, speed, and other factors. In most cases, the limit is set at a value that is a percentage of the measured value with clean filters. Typically the alarm value is set at 50% filter blockage. This value will vary greatly from one motor type to the next.

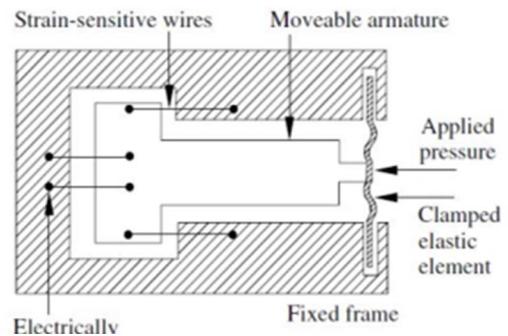


Fig. 15 (c) Pressure – Strain Gauge

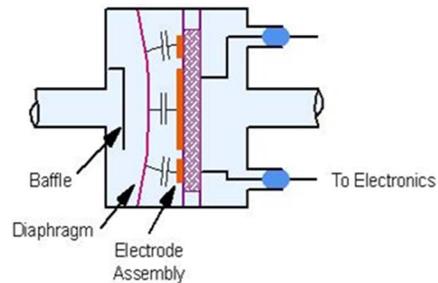


Fig. 15 (d) Pressure - Capacitive

### G. Flow Measuring Devices

There are many different types of flowmeters, and the most common are listed below.

1) *Differential Pressure Flowmeters*: In this type of flowmeter, the flow is calculated by measuring the pressure drop over an obstacle inserted in the flow path.

2) *Velocity Flowmeters*: In this type of flowmeter, shown in Fig. 16(a), the flow is calculated by measuring the velocity at one or more points in the flow and integrating the speed over the flow area.

3) *Positive Displacement Flowmeters*: In this type of flowmeter, shown in Fig. 16(b), the flow is measured by precision-fitted rotors as flow measuring elements. Known and fixed volumes are displaced between the rotors. The rotation of the rotor is proportional to the volume of the fluid being displaced. The number of rotations of the rotor is counted by an integral electronic pulse transmitter and converted to volume and flow rate.

Table V shows other monitoring devices its use, function and importance.

Table V  
Other Monitoring or Switching Devices

Device	Switch	Monitor	API 541
Flow Sensor Water	Important	Useful	Required
Ground Brush Wear Sensor	Optional	Important	when specified
Filter Pressure Differential Switch or Monitoring	Useful	Useful	Provisional required- Switch or Manometer
Vibration Switch	Useful	Useful	Not Rec.



Fig. 16 (a) Velocity Flowmeter

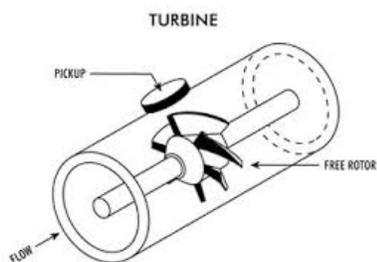


Fig. 16 (b) Positive Displacement Flowmeter

Flow measurements serve in monitoring lubrication oil flow and cooling water flow. These are mostly monitored and adjusted during commission or checked if there is a stator or bearing temperature issue.

## IV. CONCLUSION

Reliability and long-term trouble free operation are key factors in the oil and gas, process, and transportation industries. To achieve this level of reliability, it is necessary to monitor various functions of these machines. There are various parameters that need to be measured; therefore, various monitoring devices are available. Some devices can provide only an alarm and shutdown for the motor, while others can continuously give feedback. Continuous feedback is more costly but can add to reliability as well as prevent an unpredicted shutdown. Several important factors should be considered during the selection of these devices, including suitability of the media measurement, the range, the accuracy of measurement, the short- and long-term measurement drift, environment where they will be used, etc.

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