Keeping it cool: A look at causes of motor overheating

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Much has been written in EASA publications and elsewhere about the consequences of excessive temperature on a motor’s performance. We know that excessive temperature and moisture are the largest contributors to bearing and winding failures. Understanding the source of the increased temperature will help us to correct the problem and improve the machine’s life expectancy.

Figure 1 illustrates the theoretical impact of increased temperature on the life of the motor insulation system. This chart only addresses the impact of thermal aging and not various other conditions that will affect the motor’s life. In other words, it says that for every 10º C increase in operating temperature, the expected life is reduced by one-half. Conversely, if we can reduce the temperature of the motor by 10º C, we can expect the life to double. Note that this is true at any point on the curve. However, there is the rule of diminishing returns: at some point the cost of designing and operating a motor to run cooler outweighs the benefits of doing so. Here we will explore some of the factors that contribute to increased temperature.

Overload

This is a very common culprit in problems. Sometimes the overload condition is intermittent due to load variations in the driven equipment. Other times, the designer has chosen to operate above the rated load. This is actually permissible if the motor has a service factor greater than 1.0. The NEMA MG1-2011 definition of Service Factor says that a motor is thermally capable of overload to that point within the insulation class at normal service conditions (rated voltage and frequency). Of course, any overload will increase the operating temperature of the motor. Also, most motor designs will be most efficient at around 75% of rated load, so the motor will run cooler and consume less power for the same job.

The insulation class determines the maximum allowable operating temperatures to yield “normal” service life as shown in Figure 2. If the life of a motor is consistently too short in an application and little can be done to mitigate the temperature, a solution may be to rewind with a higher temperature class insulation system. Don’t forget the bearings in this attempt. The lubricant is the limiting factor in temperature related bearing problems, so be sure your lubricant will work in the environment.

Pulse width modulated (PWM) adjustable speed drives (ASD) produce negative sequence currents that essentially add load to the motor. The motor must do work to overcome these relatively low currents that are trying to make the motor run the opposite direction. The negative sequence currents also greatly increase rotor temperature. A properly designed inverter duty motor will compensate for this.

Ventilation

The motor design includes a system to carry the heat away that is produced by the winding and bearings. This is of-

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Figure 2. Maximum temperature rise for motors. (Source: NEMA MG1-2011)
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ten referred to as the “cooling circuit.” Things such as the fan diameter, shaft speed, air duct and air deflector presence and location, as well as altitude, all affect this cooling circuit.

The amount of air provided by a fan varies as the cube of the diameter and is directly proportional to the speed. Often in a totally enclosed fan cooled motor, the fan is the greatest contributor to objectionable noise. The designer must be sure the fan provides a sufficient amount of cooling air without creating too much noise.

Air ducts in larger open motors as in Figure 3 distribute the cooling air through the rotor and stator cores to improve cooling efficiency. Air deflectors may be used in open or enclosed motors to direct the air to locations that need it and to reduce turbulence. Turbulent air is not an efficient method of cooling. The location of the air deflector as shown in Figure 4 is critical to the efficiency of the cooling circuit. If the ducts are clogged or the air deflectors are missing or incorrect, the motor could run hotter.

The ambient temperature directly impacts the motor operating temperature. A motor doing a given amount of work will produce a level of temperature increase known as temperature rise. The operating temperature will be this rise plus the ambient temperature. The nameplate will have the maximum ambient temperature allowable for a motor for NEMA motors. IEC motors are limited to 40° C (104° F) ambient per IEC 60034-1 5.3. The design temperature rise at rated load plus this maximum ambient should not exceed the temperature class rating.

As altitude increases, the air gets thinner and its ability to carry heat away from the motor is reduced. If a motor is to be operated at an altitude greater than 1000 m (3300 ft) the design should be adjusted to accommodate the less efficient cooling that results.

If the motor is outdoors, the ambient temperature will be affected but some other factors such as sunshine could be a factor. In a certain case, some large pump motors were in an open pit mine in the North American Sonoran Desert. By painting the gray motors white, the operating temperature was reduced 10-15º C (18-27º F). Building a structure to shade the motors produced the same result.

Voltage

A motor is designed such that the optimum performance is obtained when the voltage applied is that which is indicated on the nameplate referred to as the rated voltage. NEMA MG1 requires the motor be capable of starting and operating at the rated voltage ±10%; IEC requires ±5%. Both standards include a tolerance on frequency that affects the voltage tolerance. For our purposes, we will consider the frequency variation to be zero. NEMA goes on to say that the motor’s performance may be affected. For instance, some manufacturers will indicate that their 230/460V designs are “Suitable for Use on 208V.” This plays on the NEMA requirement that motors be able to successfully operate at ±10% of rated voltage; 230 - 10% = 207V. If the 208V voltage supply varies, there is no margin for the motor and its per-

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formance may suffer. If the nameplate or some other communication from the manufacturer does not indicate “Suitable for Use,” it is not a good idea. The motor will produce less torque, higher full load amps, and will run hotter.

Under-voltage results in higher amperage being required to produce the needed power or work. Ohm’s Law states P=IE where P is power, I is current and E is voltage. If E goes down and P is constant, then I must go up. Since the heat produced varies as the square of the current, this additional current in the motor results in more heat produced by winding resistive losses and higher operating temperature. The slip of induction motors is inversely proportional to the applied voltage; the higher the voltage the less the slip and the faster the motor turns. As shown before, the fan will move more air at higher speeds and this will increase the power required to turn the fan. This could have as large or larger impact on the motor current offsetting a portion of the decrease in motor current.

The converse is also true: if E goes up, I will decrease when P is constant. This is one reason motors are designed with a rated voltage of 460 volts when the nominal voltage applied is 480 volts. The higher voltage helps the motor to run cooler as shown here. Care must be taken, however, in applying this principal. The magnetic flux produced in the core iron also increases. For a given electrical steel, there is a maximum amount of flux per cross sectional area. This point is known as saturation. If the voltage is increased beyond this saturation point, additional flux is possible only with a disproportionately large increase in current. The additional current generates heat. This will be discussed further in the next section.

Unbalanced voltage in a three-phase motor supply will also result in high temperatures, particularly in the phase that has the highest voltage applied. NEMA MG1 defines the method to calculate the amount of this unbalance as shown in the formula below:

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\text{% Unbalance} = \frac{\text{Maximum deviation from average}}{\text{Average}}
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This is used to calculate both the average voltage and current. NEMA MG1 states that the percent current unbalance may be 6-10 times the percent voltage unbalance. Because of this, it is important that the voltage measurement be accurate within 0.5% for all three phases. Further, with any voltage unbalance greater than 1%, the rated load should be reduced due to the additional heating.

**Electrical steel (core iron)**

A number of factors are involved to determine the ability of steel to transmit flux. The type or grade of steel, the thickness and the quantity are all factors.

Modern steels have been developed with the capability to handle higher flux levels. This is one reason higher rated horsepower can be developed in smaller frame sizes. These properties are defined in the various grades available. You might expect that the grades capable of higher flux will be more expensive, and that always figures into the design equation.

The cores for alternating current motors are laminated using thin sheets of steel stacked to produce a core. The length and diameter of this core determine its quantity or volume. The thickness of each lamination is important to control the eddy currents in that piece and ultimately the entire core. Eddy currents are circulating loop currents induced within the steel by the changing magnetic field. The thinner the lamination, the smaller the circulating loops and lower the current. These eddy currents do not contribute to the work done by the motor and are losses that just produce heat. The interlaminar insulation is...
also important to control the eddy current. If this insulation is damaged, the eddy currents can cross to adjacent laminations and become larger. This will increase the magnetizing (no load) current. The core loss test will reveal this increase and indicate that remedial action is needed to repair or replace the bad steel.

Current density

Another derivative of Ohm’s Law says P=I²R where R is resistance. In the case of a motor winding, the P here is the power that is wasted (also called loss). As wire size is decreased, the resistance per foot is increased. For a given current, the resistance of the smaller wire will produce higher P or losses. As before, these losses are manifested as heat. For this reason, it is always better to increase the total cross section of the wire per turn in an AC motor until it comfortably fills the slot. Another reason is that the resin used in the process is a better conductor of heat than air. If the slot is less than about 45% full, the resin will not be able to bond all of the wires in the slot and will leave voids. This will result in higher operating temperatures.

When designing a motor there are many trade-offs. One of these is the number of turns versus the pitch of the winding. Generally, as the pitch is increased (up to and including full pitch minus one slot) the number of turns may be reduced. With fewer turns in each coil, larger cross section of wire per turn is possible. The trade-off in this instance is the length of the end turns, especially in two-pole motors. So to optimize the design, we need to use the longest pitch practical while keeping in mind the windability and total length of turn.

Circulating currents

Circulating currents are produced in the winding when certain conditions are present. These do not contribute to the work being done by the motor and are losses that produce additional heat.

If coil groups in parallel do not contain the same number of turns as in Figure 5, circulating currents will produce high temperatures in the circuit with fewer turns or coils. In the case of odd grouping, where the number of slots per phase is not equally divisible by the number of poles, the uneven number of coils must be distributed equally through all phases. A good check is to count the total number of coils in each phase to confirm they are the same.

Two-speed, two-winding motors can also produce circulating currents. If one or both windings are connected delta or multiple parallel wye circuits, a closed circuit will be present when that winding is not energized. A special connection with four leads can open this circuit on motors connected with one delta circuit. For this to be effective, the motor starter must have four contacts rather than three. Energizing the other winding will induce a voltage in the unenergized winding and the closed circuit may allow current flow. This unintended current flow will produce additional heat in the motor. For this reason, it is always advisable to use a one-wye connection since it does not have this closed circuit. Where not possible, “The Pole-Group Connections for Three Phase Windings” table in Section 2 of the EASA Technical Manual will help identify the connections with the highest probability of success.

Harmonics

The odd harmonics of the fundamental AC (except multiples of 3) will produce negative torques when the rotor speed is above the synchronous speed for that harmonic. These negative torques are in opposition to the fundamental torque and add load thus increasing the heat. The results of the 5th and 7th harmonics to the fundamental are shown in Figure 6. These can be measured using a power quality analyzer to find the total harmonic distortion (THD) expressed as a percentage. IEEE 519 states this THD should not exceed 5% at the point of common coupling (the facility service entrance).

These harmonics are produced by non-resistive loads being supplied by the same power feeder as the motor. Motors themselves are a source of harmonics since they are mostly inductive loads. Ballasts, rectifiers, and power factor correction capacitors are a few examples of other sources.

Conclusion

The higher the operating temperature of a motor, the lower its expected life will be. Anything that can be done to lower the temperature, whether it be improving the ventilation or optimizing the design, will provide better life and reliability. For additional information on this important topic, the following Currents articles (available in the “Resource Library” of easa.com) will be helpful.

“How to Avoid Circulating Currents in Multi-Speed, Two-Winding Motors”; Cyndy Nyberg; June 2000

“Fan Law Knowledge Can Help Performance”; Chuck Yung; October 2002

“Consider Load Requirements, Applications”; Cyndy Nyberg; March 2003

“Taming Those Misbehaving Motors”; Tom Bishop; December 2009

“When It Comes to Motors, How Hot Is Hot?”; Jim Bryan; June 2011

“Cool Facts about Cooling Electric Motors”; Chuck Yung; July 2011

Editor’s Note: A PDF of this article is available in the “Resource Library” of www.easa.com.