Duty cycle for stage machinery

BY **PETE SVITAVSKY**

WHEN WE TALK about the requirements for a stage rigging machine it usually starts with the basics: How much does it lift, on how many lines, how quickly, and how far does it travel? These are examples of operational requirements that are referred to as the *limits of use*. A complete set of the limits of use includes a great deal of other information: everything from the electric supply voltage, to the means of control, and even the expected skill of the operators. The meaning of load, speed, travel, and voltage are for the most part self-explanatory, but there are other limits that may not be discussed quite as often yet are equally important to the engineers who design the equipment. A successful design anticipates not only *what* the machinery needs to do, but factors such as *where* the machine will be doing it, and *how often* it needs to be done. In this article we are going to explore the idea of "how often," known to the folks who build machinery as *duty cycle*.

Section 5 of *ANSI E1.6-1 – Entertainment Technology – Powered Hoist Systems* calls out the general requirements for stage equipment design, and it obliges the designer to design for the "anticipated duty cycles and product life." Duty cycle requirements appear again in Section 6, where the standard advises us to keep the temporal effects well in mind as we select specific components such as motors, lifting media, and even sheaves. How do we do this? What are the physical effects of duty cycle, and how do we go about creating efficient designs that are suitable for differing applications?

It's an imperfect world…

There is no such thing as a completely efficient machine. Think about your car: even with the latest models, not all the energy from the gasoline you burn goes to getting from point A to point B. A significant fraction is lost as heat from your brake pads, heat out the tailpipe, or even doing things like wearing material off your tires. Stage machines are no different. Some of the electrical power goes to moving the load, but the rest of it ends up heating up the machine or wearing down the parts. Whenever we slide or roll solid parts against each other we get friction and, by its very nature, friction converts energy into heat. Resistance is the electrical cousin of friction: it takes electrical energy and turns that into heat too. For every moment we are running our hoist there is waste heat being generated, and this heat can cause us trouble if we are not careful.

Energy balance

The machine can get only so hot before bad things start to happen. One of the most important responsibilities of the mechanical engineer is to keep track of all the energy coming in, and the energy going out, and to make plans for anything left over. We call this method of energy accounting an *energy balance*, and here is how we go about it: first, a little vocabulary. Engineers define *energy* as "the capacity to do work." That's quite a broad description, and the reason it's so broad is that energy can have many different forms. It can be mechanical, electrical, thermal, chemical, atomic—the list goes on. Also, one of the most important ideas that we work with is that *energy cannot be created or destroyed*, *it can only be transferred, or converted one form to another*. This means that whatever energy goes into a device it cannot just disappear, it is either going to come back out of the device in the same form, come out of the device in a different form, or still be within the device someplace.

Let's think about the energy balance for a typical gear motor, such as one you might find lifting a load on a theatrical drum hoist. See **Figure 1**. First, we have the energy flowing into the system in the form of electricity. We also have the *mass* of the motor and gears acting as a kind of battery: When the energy flowing in is greater than the energy flowing out, the mass gets hotter. When the energy flowing out is greater than that flowing in, it cools down. Finally, we have energy flowing out of the system, mostly in the mechanical form, but also some in the form of waste heat. I say mostly because both the motor and the gearing have a property know as *efficiency.* Efficiency is a measure of how much of the energy we put into a device comes out the other side in a useful form. If the motor is 85% efficient, then for every kilowatt of electrical power that flows into the terminals we get only 85% of that juice going out to the gears as mechanical motion. In a similar way, the reducer bolted to the motor might have an efficiency of 90%, and in that case we would lose another 10% of the power from the motor between the input and the output shafts of the gearing. Put together, only 85% x 90% = 77% of the electrical power flowing into our example gear motor would be available at the output shaft to lift the load on the hoist. That's not too bad: Some types of gearing, particularly some types of worm gears, can have efficiencies as low as 65%, meaning that almost a third of the energy coming into the reducer from the motor is wasted!

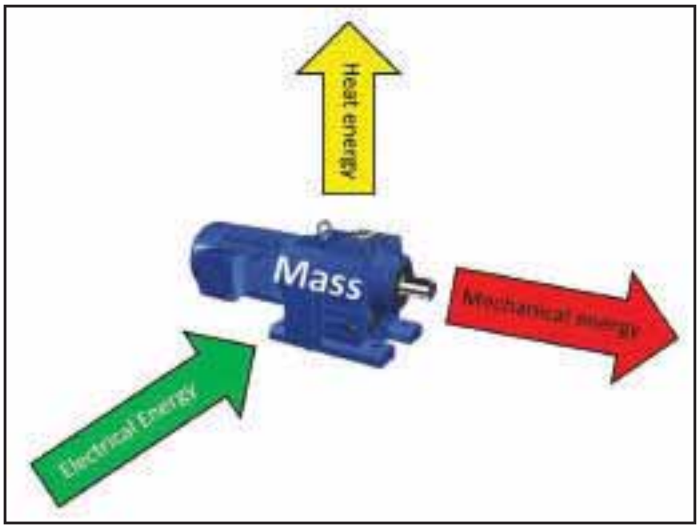

Figure 1 – Energy balance for the gear motor

So, what happens to the rest of the energy? Most of it is converted to heat by the electrical resistance in the motor windings and by the friction in the gear reducer. We must get rid of the wasted energy as fast as we make it, or if we run the machine too long the temperature of our machinery is going to continue to rise and eventually cause damage.

Managing the waste heat

The most common way to get rid of waste heat from a motor on stage is to transfer it into the air surrounding the machine. If the amount of waste heat is modest, and the surrounding air is not too hot, we can let Mother Nature do the work for us with natural convection. If we have too much heat for natural convection, we can add a fan to blow cool air over the motor. If we can get the heat to flow out from the motor as fast as the inefficiency can create it, then we can run that motor indefinitely and it will never overheat. Running a motor in this way is called *continuous duty*. In a continuous duty application, we can remove the heat from the motor at the same rate it is being generated.

Another way to manage the waste heat is to stop making it so fast, i.e. turn it off for a little while and let the machine cool down. Motors are designed to operate at a certain elevated temperature without being damaged, so if we start from cold, we do have some operating time before that mass absorbs enough energy to become overheated. If we don't want to use a fan to remove the waste heat, or if the heat is being generated faster than our fan can pull it off, we can just shut the motor off before it overheats and let the whole thing cool down. Operating a motor like this is called *intermittent duty*, or a *thermally limited design*.

Matching the duty to the application

When a designer selects a motor for a given application they must choose between intermittent or continuous duty. In some applications the choice is made for us, because the customer does not want to have to shut off the machine and let it cool. For instance, if a soda plant was required to shut off the bottle capping machines every 20 minutes and let them cool down for 10 that would not be a very productive plant! However not all machines need to run continuously. Consider a common application in the theatre industry, namely the house curtain in a typical high school theatre. Let's say tonight they are putting on a talent show, i.e. a two-hour string of short acts tied together with some introductions by a master of ceremonies. It takes ten seconds to open the curtain to reveal a talented young person who then belts out a tune in about two minutes. The crowd applauds, and the parents snap some photos as our machine drops the curtain again. The MC tells a joke for another minute as the stage crew sets the next act, and then the cycle starts again. Here is the basic duty cycle for our curtain machine:

$$\text{Duty Cycle} = \frac{time\ on}{time\ on + time\ off} = \frac{10\ sec + 10\ sec}{10\ sec + 10\ sec + 120\ sec + 60\ sec} = 10\%$$

Energy is flowing into our system only 10% of the time, and the other 90% the motor is quiet and cooling. Ten percent may not seem like very much, but it's one of the more demanding applications for the stage equipment you might find in a small theatre. Think about how often the fire curtain hoist runs. Considering that many of our stage machines are running 10% of the time or less, intermittent duty motors can be an attractive option.

Advantages of intermittent duty motors

Intermittent duty motors have some features that make them well suited for stage equipment. First, many theatre applications are noise sensitive and fans make a good deal of noise. If we want our hoist to be quieter, we may be able to use a big enough motor, design it for intermittent duty, and then not use a fan at all. Even though the motor is not being cooled by a fan, the short duty cycle keeps the motor from overheating.

Another attractive feature of intermittent duty motors is that, for a given horsepower, they are generally smaller and lighter than their continuous duty cousins. This helps control the costs of manufacturing and installation, and it can also help make the equipment more portable.

Finally, a more subtle benefit of an intermittent duty motor is a reduction in stalling torque. Consider the motor curve seen in **Figure 2**. For this type of motor you can see that, generally speaking, as more load is applied to the motor shaft, the motor will slow

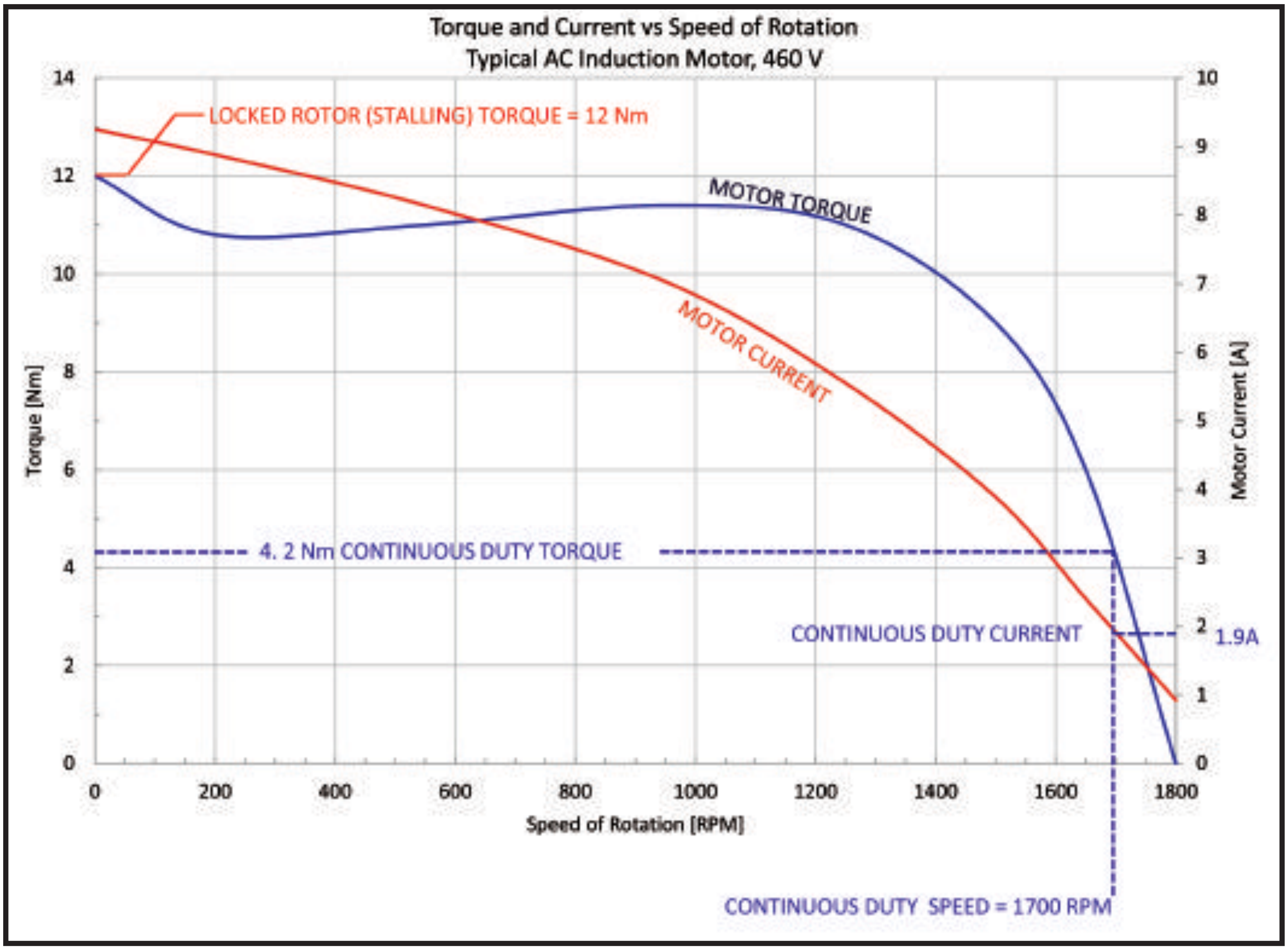

Figure 2 – AC motor curve, continuous duty

down and the current draw goes up. The current is the source of energy, and so as we draw more current we generate more waste heat. The 1.9 A of current is the most we can put through this motor continuously without having to stop and let it cool down, and it will generate 4.2 Nm at 1700 RPM all day long. This is the continuous duty operating point.

Now, on that same curve you can see that the motor is capable of making much more torque if we are willing to put more current through it. However, if we do this the motor will slow down and start to heat up too. Look at **Figure 3** and you will see the curve of the same motor, but now we are loading the motor shaft to 5.5 Nm. It's now drawing 2.3 A, and that extra 0.4 A will generate more heat than the motor fan is capable of shedding, so we must stop periodically and let our motor cool in order to avoid overheating. This is an *intermittent duty operating point*.

Look in the upper left-hand corner of either chart and you will see the absolute maximum torque that this motor is capable of making; it occurs when the output shaft is not rotating at all, i.e. zero RPM. We call this the *locked rotor torque*. This number is important to hoist designers because it is part of our job to ensure that the machines we design can resist the greatest force our motor can produce. Consider the same motor rated for both continuous and intermediate duty, **Figures 2** and **3**, respectively. If we look at the fraction of the stalling torque vs the rated torque in both cases we see:

$$\text{Continuous duty stalling torque ratio} = \frac{12.0\text{ Nm}}{4.2\text{ Nm}} = 2.9$$

$$\text{Intermittent duty stalling torque ratio} = \frac{12.0\text{ Nm}}{5.5\text{ Nm}} = 2.2$$

This is a significant reduction in the amount of torque that our machine must withstand if there is an accident or misuse, and for simpler machines that do not take advantage of variable frequency controllers, it can result in a reduction in the required strength and size of the machine components. See more on this topic in the article "Load Cases for Stage Machinery Design," *Protocol*, Fall 2019.

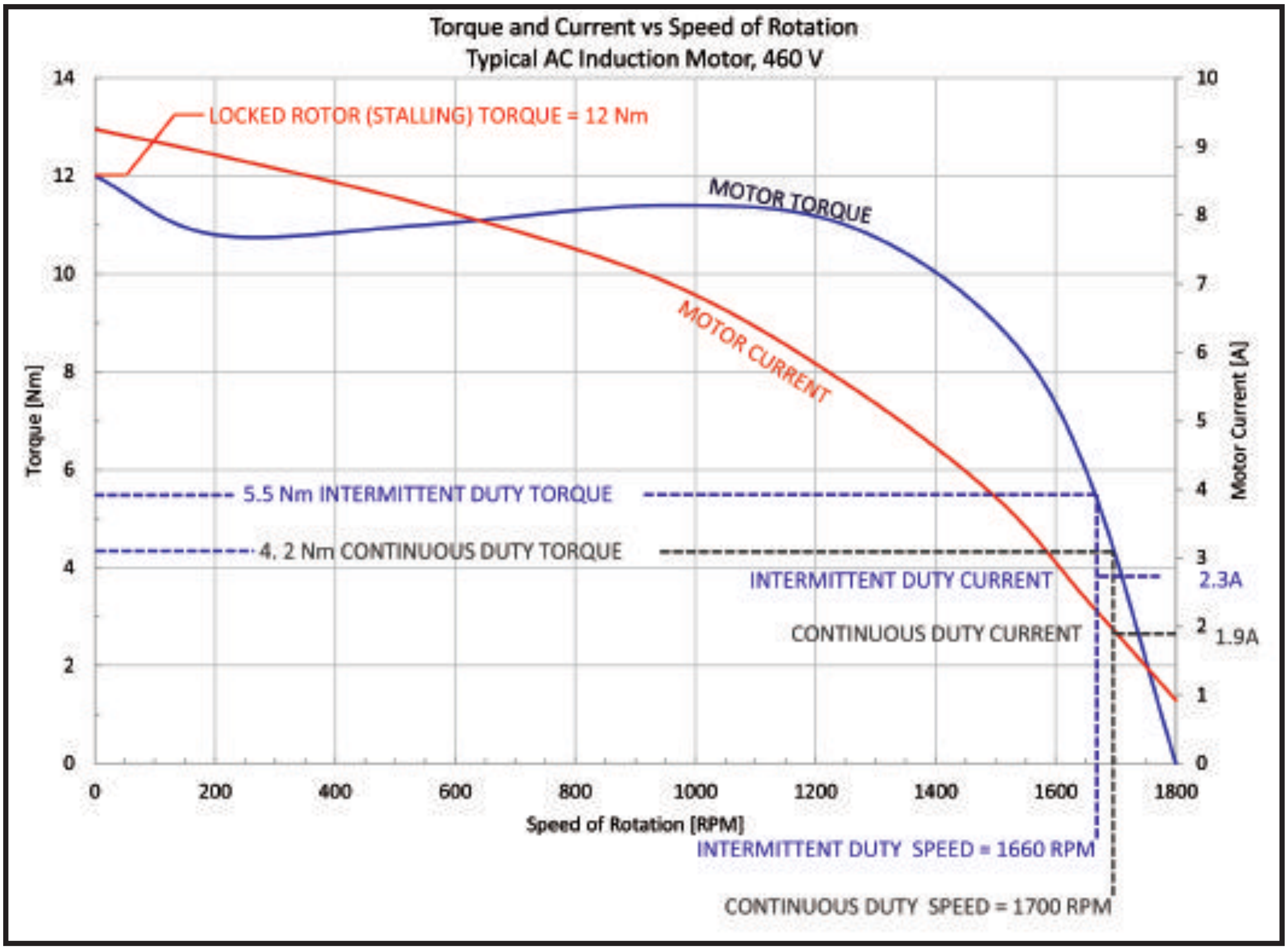

Figure 3 – AC motor curve, intermittent duty

You can get the sense from these figures that, in order to operate a motor for intermittent duty, the motor manufacturer has to do quite a bit of product testing to understand exactly how much current and torque can be put through a particular motor and for exactly how long before it overheats. Not all motor manufacturers rate all their products for intermittent duty. As we see in the example above, it is possible for the same motor to have multiple ratings depending on the duty cycle. In practice, manufacturers often create entirely new designs for their thermally limited motors, optimized with features such as larger shafts and different windings.

We have seen a measurement of duty cycle based on operating time, but there are a number of different duty cycle descriptions that capture not only the fraction of operating time but other important variables such as how many times the machines starts per hour and how cool the motor is allowed to get between cycles. You may see these described on motor labels using the codes S1, S2, S3, etc.—and the exact meaning of these can be found in standards such as *IEC 60034*. When we design for continuous duty, and then operate at intermittent duty as we have often done for the stage, we have plenty of extra torque available to accommodate these other factors. However, when we optimize our motor for the exact duty cycle, it is incumbent on the designer to make sure that all these additional factors are considered in order to ensure a successful design.

Finally, it's worth noting that the curves we have been using in our examples so far are particular to one common type of motor, namely AC induction or "squirrel cage" motors. There are other types of motors used commonly in stage equipment, and they are very often designed to be thermally limited. *Permanent Magnet Servo Motors* can be found in many modern stage equipment designs, and despite being relatively expensive, they are popular for the reasons we have discussed: lightweight, small, and powerful. Servo motors are designed to be optimized for intermittent duty applications. Manufactures typically publish curves not only for the torque vs. the motor speed, but also curves that show exactly how much power they can put out and for how long before they overheat. Using these tools, in conjunction with a well-defined duty cycle, the engineer can identify the smallest possible motor that is strong enough and can operate without overheating in each application.

Conclusions

The practice of designing with continuous duty motors to be used for intermittent duty applications is a conservative approach. The excess of power and thermal capacity provides comfortable assurance in the case of bespoke engineering projects where extensive analysis and testing may not be practical. The cost of this assurance comes in the form of the additional cost and weight of the motors, and also the cost of the stronger machinery required to accommodate the power of the oversized motors. On the other hand, careful consideration of the duty cycle, in combination with thermal design data becoming ever-more available from motor manufacturers, can result in *ANSI E1.6-1*-compliant designs that are increasingly more efficient, and efficient designs appear to the theatre owners and operators as economy and ease of operation. As many segments of the theatre equipment market continues to transition from bespoke engineering to serial manufacture these benefits can continue to be realized. ■

Peter V. Svitavsky, P.E. has worn a number of hats at JR Clancy and Wenger Corporation over the last twenty years working on stage engineering projects around the world. He is a licensed Professional Engineer, inventor of several patented designs, and proud to be among the members at USITT and ESTA who work to develop national standards for the entertainment industry. He is a regular contributor to the education of future generations of industry professionals through classes and conferences. When he is not working on stage machinery you will find him with his family at home in the Finger Lakes or prowling in the woods and fields of Upstate New York.