HEAVY MOVABLE STRUCTURES, INC.
SEVENTEENTH BIENNIAL SYMPOSIUM

October 22-25, 2018

Motor Upsizing

Megan Tatara, P.E. and Joseph Jacobus, P.E.
HDR Inc.

MARRIOTT’S RENAISSANCE HOTEL AT SEAWORLD
ORLANDO, FLORIDA

Executive Summary

The electric motor is a key component for heavy movable structures and is the transition point where the mechanical system meets the electrical system. The electric motor converts electric power into torque or hydraulic energy and is used on a majority of movable structures throughout the world. Some of the heavy movable structures that use electric motors are roadway, railway, and pedestrian movable bridges; barge and ferry transfer bridges for rail, cars, or pedestrians; water flow control devices; and canal locks. As these structures age, they experience higher loads due in part to wear and deterioration of the structure as well as increased dead loads, live loads, and hydraulic loads. Increased loads result in increased motor amperages which can prematurely degrade the electric motor.

One solution employed by owners is to install a larger motor to handle the increased loads. While this addresses the problem at the source, upsizing the motor has unintended consequences. The machinery and structure should have been designed for the maximum output of the original electric motor to prevent permanent damage in the event that the structure becomes jammed and the motor drives to its locked-rotor torque. Upsizing the motor could cause catastrophic damage unless appropriate measures are taken to protect the mechanical, structural, and electrical systems.

The following paper will discuss issues that may arise from upsizing a motor and techniques that can be used to mitigate these issues. Some of the topics that will be discussed to better understand the issues are proper design of machinery per industry codes, torque limiting techniques, motor types, types of motor control, and some scenarios where upsizing the motors was considered. The objective is to give the reader a general understanding of the issue of motor upsizing and aid in making informed decisions regarding rehabilitation of heavy movable infrastructure.

Introduction

Motor size is one of the key components to operating heavy movable structures. A motor that is too small will not move the structure, but a motor that is too large can have unintended consequences, such as potentially damaging equipment by providing too much force in certain scenarios. This paper reviews the factors associated with motor sizing, machinery design, and motor control techniques and analyzes real world cases where motors were suspected to be sized improperly based on motor current measurements during operation.

Machinery Design

Design manuals help develop the basis of design for heavy movable structures. The common design manuals used are AASHTO for highway bridges, AREMA for railway bridges, and USACE design manuals for flow control and marine navigation structures. Each manual has information specific to its respective industry, but there are many areas of overlap, especially for machinery design. Within these overlap areas, each manual may take a different approach to design of components.

A closer look at the design of a machinery shaft will help highlight the differences between the design manuals. Machinery shafts are typically subject to both alternating stress in the form of bending stress and constant stress in the form of torsion. The alternating stress happens when a shaft is subject to a direct load such as a gear mounted on the shaft. Stress in the material goes from tension to compression every 180° as the shaft turns. It is possible for a shaft to fail when subject to many cycles of an alternating stress, but would not fail when subject to the same constant stress. This type of failure is known as fatigue. The factors that effect fatigue stresses are material size, surface finish, radii in shaft steps or keyways, and material irregularities. A simplified example of a fatigue failure is bending a paper clip back and forth until it breaks.

The 2015AREMA Design Manual determines the maximum shear and tensile stress using the von Mises stresses when subject to 150% full load torque of the motor with a factor of safety (FOS) of 5:1 on the ultimate tensile stress of the material. It is stated that the stresses specified provide appropriate safety factors against static failure and against failure by fatigue with and without reversal of stresses. In the determination of the safety factor against fatigue failure, provision was made for stress-raisers which would produce local stress concentrations of 1.4 of the computed stress. It is common for stress concentrations at keyways and shaft steps to be greater than 1.4. The engineer may decide to use a more conservative approach and increase the stress concentration factor based on the actual geometry.

Some of the earlier versions of AASHTO followed a similar method as described in the preceding paragraph. The 2015 AASHTO Design Specifications uses the Goodman distortion energy (DE) formula to size shafts with 100% full load torque of the motor. The DE method compares the alternating stresses with the endurance limit stress of the material and the constant stresses with the yield stress of the material. The two are then combined and must be greater than an FOS of 1.25. The endurance limit is a function of the ultimate tensile stress of the material, diameter, surface roughness, temperature, and reliability of the material. The DE method prescribed in AASHTO is generally a more conservative than the method prescribed in AREMA.

The USACE Engineering Manual (EM) titled, “Mechanical and Electrical Design for Lock and Dam Operating Equipment” (EM 1110-2-2610), uses the same method described in AASHTO with some modifications. The EM uses a 20% of ultimate tensile stress in lieu of the endurance limit stress and an FOS of 1. The method also uses the ASME Elliptical DE method, which differs slightly from the Goodman DE method. The EM also requires the engineer to check components for the overload case using 75% yield. The purpose of this check is to prevent the machinery components from permanent damage due to momentarily extreme loading.

When deciding whether it is appropriate to increase a motor size to gain operating capacity, an analysis of machinery should be performed. It is advisable to use a conservative approach when designing new machinery, but it is also important to use engineering judgment when analyzing existing machinery. AASHTO may be too conservative resulting in a greater scope of replacement in rehabilitation and greater cost. A less conservative approach may be more appropriate. One approach could be to use the method described in EM 1110-2-2610, including the overload case. It is very important to communicate any deviations from the industries respective manuals with the end user and what risks are associated with the deviations.

Contributing Factors for Higher Loads

Increased loads can be from a variety of sources. Some sources are due to aging equipment, while others are due to changes in equipment during past maintenance or rehabilitation work. The impact of the change in loads varies depending on the location of the load change relative to the prime mover.

When steel corrodes, the volume of the material becomes larger. The increase in volume moves the structure or machinery from the original location. The impacts of this can be seen in different ways in different pieces of equipment. For instance, if the shims of a motor become corroded, the motor may move out of alignment with the machinery and create higher friction loads during operation. Places where two pieces of machinery meet can wear away material over time during operation. This scenario creates additional space between pieces of machinery and causes misalignment. Friction from wear will change the loads experienced by the motor and throughout the machinery system.

Change in dead load can be a result of equipment replacement on the structure, such as structural members, machinery, electrical equipment, or other ancillary equipment, such as equipment enclosures and control house modifications. For example, with movable bridges, there can be increased dead load when the deck surface is replaced with a heavier substitute to improve rideability These changes can result in an overall increase in load. This change could alter the way torque is generated by the motor and transferred through the machinery to the structure.

Motors

Heavy movable structures are typically operated by an electric motor. The motors used vary by industry, but modern motors are typically NEMA-style motors. Original motors on structures built prior to approximately 1930 typically are not NEMA-style motors and may consist of DC motors. Some structures may use IEC-style, NEMA-style motors. Modern motors are typically NEMA D-style or NEMA B-style. NEMA B-style motors have high locked rotor torque, while NEMA D-style motors have very high locked rotor torque and higher slip capabilities than NEMA B-style motors. Both NEMA B and D-style motors have low starting torque. NEMA D-style motors are well suited for equipment with high inertia starts such as heavy movable structures, but NEMA B-style motors can be used also if the engineer considers the application and reviews the speed-torque curve for the desired motor when designing the mechanical system; the review may include comparison of the speed-torque curve for the proposed motor to the speed-torque curve for the original motor if the structure has not significantly changed since the original installation.

It should be noted that when replacing a NEMA D-style motor with a NEMA B-style motor, the overall performance of the motor must be considered. Replacing a NEMA D-style motor with a NEMA B-style motor of the same horsepower will not result in the same performance. NEMA D-style motors utilize the high torque at low speed characteristics to begin movement from a stationary position. A NEMA B-style motor may need to be approximately twice the horsepower rating of a NEMA D-style motor to achieve the same torque at zero speed. These performance characteristics occur regardless of the type of motor controller used.

In addition to motor types, some specific features of motors are typically identified. Each motor has a nameplate with pertinent ratings:

- The full load amperage (FLA) is the amperage of the motor when full load torque and horsepower are reached.

- The locked rotor motor code determines the multiplication factor of the FLA to determine the anticipated inrush on startup or other times of locked rotor. Motor code is typically F through L for heavy movable structures. These codes result in a range of 5.00 to 9.99 times the FLA at locked rotor.

- The time rating determines how long the motor can be operated before needing time to cool down. Depending on the duration and frequency of operation, a motor for heavy movable structures may be rated for a specific time period (such as 15 minutes, 30 minutes, or 60 minutes) or continuous duty (which does not need a cool down period before its next operation). As a note, continuous duty is considered to be constant operation, not frequent starts and stops; frequent starts and stops generate higher current during inrush and can wear out the motor more quickly than continued operation.

- Insulation class impacts the ability of the motor to handle temperature rise above the ambient temperature. This factor is important when motors experience higher amperages than the intended current range, which results in higher temperatures generated within the motor. The insulation class of the wiring within the motor determines how much temperature increase the motor will be able to handle.

- The service factor may be 1.0 to 1.15. This factor allows for a motor to operate above the FLA for a short period of time. Per NEMA MG 1 for motors with a service factor of 1.15, “operating 1 hour at specified 1.15 service factor temperature-rise values is approximately equivalent to operating 2 hours at the temperature-rise values specified for a motor with a 1.0 service factor.” It is typical industry practice to size the motor and associated motor control devices based on the FLA rather than the service factor applied to the FLA.

Motor Controllers

Motor operation is controlled by a variety of devices. Typically, the device chosen is based on the type of motor installed and the type of operation needed for the application.

NEMA D-style motors are typically controlled by a motor starter. The motor starter provides power to the motor and controls which direction the motor turns. Where variable speed is required, such as movable bridges, secondary resistors are used to change the speed of the motor, which correlates to changes in torque capabilities. At higher resistances, the motor is able to put out higher torque and spins at a slower speed. This method of operation helps the heavy movable structure develop sufficient torque to begin moving from a stationary position. As the structure begins moving, resistance can be removed from the motor control circuit so the structure can move faster with lower torque being applied by the motor. Typically four to six sets of resistors are provided, resulting in four to six different speed steps available to the operator. Occasionally soft starters are used, which reduce the voltage to the motor during start up; soft starters are typically used when motor speed is not controlled, such as for dam gate operation.

NEMA B-style motors typically use variable frequency drives (VFDs) to control the motor. VFDs can provide a number of limits on the motor, depending on user settings. The VFD can be programmed to control the operation of the motor by monitoring current, torque, or speed and adjusting the motor operation automatically, called a closed-loop system. An infinite number of speeds are available with a VFD. A VFD can also be programmed to allow the operator to control the speed of the drive, similar to how speed is controlled with resistors, called an open-loop system.

Some older movable bridges are controlled with stepped resistance and a drum controller, which is the system described in the paragraph for a NEMA-D style motor. The stepped resistance allows the operator to select a resistor that manipulates the speed torque curve. Stepped resistance requires operator feel to safely operate the bridge. When existing motors are replaced, the designer sometimes elects to upgrade to a VFD motor controller. The engineer should consider capacity, condition, and smooth versus uneven operations of existing machinery. VFD controllers require a complex set of parameters to be programmed and could present challenges if some of the conditions above are adversely present.

Torque Limiting

To prevent excessive torque from damaging mechanical or electrical equipment during operation, torque limiting devices can be used. Torque limiting devices consist of electrical and mechanical means. The common aspect to both mechanical and electrical torque limiting devices is that they introduce additional equipment to the operating system that must be maintained. Some equipment requires more maintenance than others, but the device must be operational to properly limit torque and should be tested regularly to verify that the device operates within the intended parameters.

A shear pin is a mechanical device where a sacrificial component (the pin) disconnects the operating machinery from the motor. This device does not stop the motor, is not adjustable, and does not provide the control system or operator any indication that the pin has failed; the operator must monitor the condition of the machinery during operation to determine if the pin has failed. Also, the pin is a consumable product that must be replaced when torque is exceeded before operating the structure, even under appropriate torque levels. The location of the shear pin needs to be such that the structure's inertia can be controlled or, in the case of a gate, the hoisted load can be held in place.

A friction clutch allows the machinery to slip when torque is exceeded. This device does not stop the motor but is adjustable and allows the machinery to re-engage when appropriate torque levels are achieved. Friction clutches do not provide the control system or operator any indication that the clutch has exceeded the desired torque; the operator must monitor the condition of the clutch during operation to determine if the torque has been exceeded. Friction clutches rely heavily on a constant and reliable coefficient of friction. It is important to keep all surfaces free of corrosion and lubricants to operate properly.

Soft starters limit torque, but only during start up and stopping. These devices are not appropriate for use to limit torque during operation, such as an object being caught within machinery and impeding normal operation.

Other electronic devices, such as overcurrent monitors, initiate when current is sensed then begin a time delay to inhibit the sensor during inrush. After the time delay, the device allows the motor to operate during normal current levels but stops the motor if high current is sensed. Caveats include the time delay nature of the device, which could damage machinery to some extent before the time delay stops operation. Also, current does not exactly correlate with torque, so this is an inexact method of limiting torque. Overcurrent protection can also be adjusted in the future by personnel if the protection is consistently tripping resulting in an operational nuisance. The personnel may not be aware of the history behind the installation and the appropriate setting of the overcurrent protection when making adjustments, which may result in damage to machinery components if it is adjusted to an inappropriate setting.

The user must weigh these various devices to determine which device is best for the specific application, or whether the ongoing maintenance and testing of the device outweighs the potential benefits of the device. The best method for load limiting is to design a system in which the motor's maximum output torque is less than all machinery components' capacities.

Case Study Examples

One common field where motor upsizing has been considered is dam gate hoists. Many dam structures were originally designed and built in the United States in the 1930s and 1960s to produce electricity in the West, Pacific Northwest, and Southeast as well as water retention for irrigation and flood control. Many of these structures contain most, if not all, original components that have begun to deteriorate due to their age. A dam built in 1968 would be 50 years old today, with mechanical and electrical components well past their anticipated useful life and manufacturer warrantee period.

Dam Gate Hoist Inspection Overview

Recent inspections of these structures have been performed in accordance with FERC Engineering Guidelines for the Evaluation of Hydropower Projects, Chapter 14 Dam Safety Performance Monitoring Program, Appendix L Detailed Radial Gate Inspection Reports. These guidelines require "[the] inspection team [to] observe each gate moving through its full range of motion, fully closed to fully open and back, and provide observations and comments. If the requirement for a full open test does not coincide with the year of the GIR [Gate Inspection Report], it is acceptable for the GIR to include a review and comments on the previous full open testing, provided there is sufficient documentation available from that test for the inspection team to make an informed conclusion regarding the operational condition of the gate (e.g., real-time power draw plots, video with audio, etc.)". Each inspection should record current and voltage on all phases during the full range of operation with a power analyzer per the requirements above. Video of the gate should also be recorded for each operation to document any visual or auditory anomalies noted during the inspection; field notes should be taken, describing any discrepancies, for ease of reference.

During four recent dam gate hoist inspections, it was noted that all motors are operating near or above FLA during gate opening after inrush current has subsided. The chart below summarizes the findings for each of the sites:

Site	# Gates	Motor Type	Motor Vintage	Gate Raise Current[1] (% FLA)	Gate Lower Current[1] (% FLA)
Site A	5	Non-NEMA (Shop Hoist)	Unknown[2]	70-122	54-65
Site B	6	NEMA B	1968	88-178	47-65
Site C	33[3]	NEMA C	1960	85-109	44-46
Site D	3	NEMA D	1967	62-110	36-57

Notes:

1.) Wider ranges of % FLA generally correlate to lower horsepower motors (and subsequently lower FLA). Values include the lowest of the three phases and the highest of the three phases of all gate operations. Values do not include inrush current.

2.) It is assumed that the hoist motor was installed before 1999 (earliest motor current measurement and motor nameplate information available) but after construction (latest shop drawing/as-built information notes 1917). It is expected that the hoist motors were replaced in the 1990s.

3.) Two gates of the 33 were tested. Two mules were available on site; each mule was tested once with two different gates.

General Gate Operation Observations

Based on typical modern engineering practice for motor sizing, the motors are expected to be operating at approximately 80% of the rated horsepower while the electrical current measurements taken in the field showed that the motors are operating over the rated nameplate FLA. Each instance had voltage within nominal (less than 10% deviation from the expected voltage). Each instance also had similar current readings, generally within 10-15% between numerous gates under similar conditions. Environmental temperature, overall weather conditions, and differences in frequency of operation may have contributed to some minor deviations, but in general, trends held consistent with operation of each gate.

At Site B, different lubrication techniques were attempted, such as lubricating during operation compared to lubrication before operation begins, but resulted in similar measurements; one exception was when the gate was not lubricated at all, which resulted in the highest current measurements of all of the gates.

Historical measurements at various sites, including the sites listed above and others, show that the gate with the highest amperage reading is not consistent each year (for example, in the first year, Gate 1 has the highest amperage reading; in the second year, Gate 3 has the highest amperage reading; etc). In general, the historic data was taken with only one phase, at a gate height that is unclear and potentially inconsistent each year, and other details missing that may have provided insight into the varying results.

It is unknown what the design philosophy was for dam gates in previous decades, particularly in the 1960s for Sites B through D in the examples above. The guidelines of the day may have dictated that the current required to operate the motors is within the expected operation of the gates. This consideration does not entirely resolve the issues because in some cases current measurements are generally trending up (i.e. increasing throughout the years). Also, many details on how the historical data was collected is unknown, leading to doubts when comparing measurements from one year to the next.

FERC Impacts

Many FERC representatives have become concerned with the measurements at many gates being above FLA. This concern is what prompted the development of Appendix L noted above. However, it is anticipated that the thought process behind the concern may be misguided. One of the potential reasons that current measurements are being scrutinized is the idea that measured current is equivalent to torque to operate the gate. However, current is not directly correlated to torque. There are losses in the motor and machinery that contribute to a difference between the current value and the torque applied to moving the gate. Attempting to determine the exact torque observed by the gate based on current measured by the motor will provide inaccurate results.

The following are potential reasons for the increased amperage based on review of the four sites noted above; this list is by no means an exhaustive list of all potential or actual causes of increased amperage.

Motor Degradation

In scenarios where motor degradation is a concern, there may be some similarities as well as differences between different motors in terms of operation. Assuming the motors in question were installed at the same time, there will be some similarities based on the motors being installed in a similar environment. However, it is expected that motor performance would differ more greatly between gates, particularly between those operated frequently and those operated less frequently. Also, if maintenance is not performed consistently between the motors, this may lead to differences in speed of motor degradation; for instance, if any motor openings or penetrations have not been sealed properly, moisture infiltration may be an issue at some motors but not others.

Current imbalance should be considered in addition to high operating current and is another sign of motor degradation. If voltage is balanced (less than 10% imbalance) and current imbalance exceeds 10% during operation, there may be damage to the motor. Typically, current imbalance will occur at different rates and on different phases even with motors of a similar vintage that are installed in the same environment. In these scenarios, it is recommended that dynamometer testing be performed or the motor be rewound or replaced, depending on which option is more cost-effective.

Operating the motor above 80% of FLA may lead to long term deterioration of the motor due to excessive heat buildup. However, if a motor has an appropriate duty cycle for the application, has a service factor above 1.0, and is operated infrequently (such as a few times each year), it is expected that damage from exposure to the elements may contribute more wear on the motors than operation at high current levels. Frequent operation over FLA will begin to degrade the motor insulation eventually, particularly if the motor is not given adequate time to cool down between operations; at this point, operation over FLA will continue to damage the motor insulation with each operation and may result in continued increasing current measurements over time due to the motor insulation damage. Typical operation of the motors for water transfer should not cause the motors to overheat, but there is a potential for overheating during inspections where the motor is operated in the event that there is a malfunction or error by the operator or inspector. In this case, the gate may be lowered from a partial opening and opened again immediately which may cause overheating of the motor, depending on the duty cycle and other characteristics of the motor.

Friction

An increase in friction over the life of a structure is expected. Areas where friction increases have the highest likelihood of increasing current measurements include trunnions, side seals, and operating machinery. It is expected that each of these sources will differ between gates of a single structure, particularly between those operated frequently and those operated less frequently. Inconsistency with maintenance practices may also vary the magnitude of friction differences; a structure that is kept well maintained may experience less increase in friction compared to a structure that is not maintained as frequently and consistently.

Lubrication techniques should be reviewed to confirm that the type and quantity of lubrication being used is appropriate for the application. Prior to operation, it should be verified that the machinery is properly lubricated to reduce the potential of machinery causing high current loads. If a gate will be operated when not holding water, it is advisable to apply water to the gate seals approximately 5-10 times or approximately every 5-10 minutes during operation, depending on the speed of operation. If the duration of gate operation is less than 5 minutes, it is advisable to wet the seals during the entirety of the operation.

Operation and Maintenance Practices

Proper protocols should be followed during operation. Issues noted at the sites above include operating hoists past the fully closed position to leave slack in the ropes. This procedure can cause kinks to develop in the ropes. A suggested practice is to operate the gate until it is fully seated and only a short period of time past the fully seated position. The operation time to achieve this is typically one second or less past the fully seated position; for some gates with an operation time of less than 5 minutes, a second may be far too long to operate past the fully seated position. In order to automate this practice, slack cable limit switches can be installed. These limit switches can be connected to the control system to stop motor operation in the event of detecting a slack cable scenario.

Operators should monitor for the gates “chattering” or other visual or auditory signs of structural or mechanical issues and record the gate height and time when they occur. This documentation will allow comparison of operational issues against motor current measurements to identify any correlations between current spikes and the field notes. These issues are likely not to be resolved by increasing motor size; rather, these issues require investigation into the specific mechanical and structural systems to determine the cause of the operational distress. Specific repairs should be made to the actual source(s) of the problem after in-depth inspection and testing to identify the exact components requiring rehabilitation. In some instances, upsizing the motor is warranted, but it is not required and could even cause additional problems in other situations.

Conclusions

Increasing the size of the motor for heavy movable structures should be done with considerations to the structure and machinery as a whole. It is important to understand the implications and the risks when doing so. Some questions that should be answered before increasing the motor size should be:

- What is the root cause leading to the need for a larger motor? Some responses could be:
    - The motor was undersized during original design.
    - There is increased friction due to wear or machinery misalignment.
    - The motor has degraded.
    - Appropriate maintenance practices are not being performed in a timely manner.
- What are the impacts to existing machinery? This aspect requires analysis and potential modifications to accommodate the larger motor. When machinery components are subject to loads above industry standards (AASHTO, AREMA, and USACE), the risk of component failure increases.
- What are the cost and safety implications of a failure caused by the motor producing too much torque for the application? Can a contingency plan be put in place to limit down time?
- Is the cost associated with addressing the root cause less than the costs associated with a failure caused by the motor producing too much torque for the application? This consideration includes operational losses due to down time and emergency repairs, damages to stakeholders, and fines by regulating agencies.