HEAVY MOVABLE STRUCTURES, INC.

NINTH BIENNIAL SYMPOSIUM
"Preserving Traditional Values with New Technologies"

OCTOBER 22 - 25, 2002

LOAD SHARING FOR MOVABLE BRIDGE MOTORS AND DRIVES

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ELECTRICAL/ELECTRONIC SYSTEMS

Introduction

For over a decade, papers have been presented at the Heavy Movable Structures symposia discussing the merits of various motor and drive combinations for movable bridges. Much of what has been presented was work in progress or what amounted to a sales pitch. The purpose of this paper is to present a decade of examples of what has worked and what has not worked, as advertised, in the way of motors and electronic drives on movable bridge applications. Although the discussions are pertinent to all types of movable bridges, most of the examples are for bascule bridges. The dynamics of a bascule bridge accentuate the problems associated with load sharing. This is especially the case for electronic motor controls.

Load Sharing Defined

Load sharing can be defined as the torque required to operate a movable span, divided by the number of elements providing input torque to the system. If there are two drive motors, each motor should be providing one half of the input torque. If two pinions are providing torque to the leaf racks, each pinion shaft should have equal deflection. Further, most designers would agree that this sharing of the torque would be for the duration of the operation. Therefore, for purposes of this discussion, load sharing is defined as equal torque, measured on the pinion shafts, for the entire range of operation.

Mechanical Load Sharing

In the earliest movable bridge designs, load sharing was accomplished with differential reduction gear. Two drive motors were typically connected to a common input shaft of a differential reduction gear. The motors were usually on separate contactors, but operated together by common control relays. From this single reduction machinery, the torque was transmitted to the drive pinions via line shafts and secondary reducers. The leaf drive pinions were connected to the output shafts of secondary reducers. Thus, the differential reducer accomplished load sharing between the pinions, mechanically.

Since the load sharing is accomplished mechanically, a single motor can operate the machinery. Motor control is simple direction, speed, and torque control.

- <u>Main Street Bridge in Jacksonville, FL</u> is one of the largest span drive, vertical lift bridges in the country. It was rehabilitated in 1992. The original motors and machinery were replaced with an enclosed differential reducer with two 200 hp d.c. motors. Each motor is driven by an Allen-Bradley four-quadrant, regenerative SCR (silicone controlled rectifier) drive. The bridge is normally operated on a single motor with the other motor and drive as an off-line backup. The control logic automatically alternates the motors for even wear.

  The drive system was the designed and fabricated by a value added controls contractor working very closely with a local factory representative of the SCR drives. Although there were minor logic problems during start up, the motor drives were set up and operating correctly within a single night.

- <u>Montlake Bridge in Seattle, WA</u> was rehabilitated in 2000. The original series wound d.c. motors and machinery were refurbished and reinstalled. The motors are connected to a common input shaft of a differential reduction gear system. The machinery is behind the counter weight and power is transmitted to the main drive pinions via line shafts, bevel gears, and a secondary reduction line. The motors are split case traction motors, each capable of driving the leaf. The resistor and control relays were replaced with Siemens regenerative SCR drives. Because the motors were series wound, the single quadrant drive was used for the field. The combination of single and four-quadrant drives caused the series motor to behave exactly as a shunt wound motor on a four-quadrant drive. The drives were set up to operate the leaf on a single motor with an off line back up. The drive system was designed, fabricated, and set up by a value added controls contractor with business ties to the drive manufacturer. The motor drive set up and tuning was accomplished in a single night.

- Hallandale Beach Boulevard Bridge in Hallandale, FL is a new four-leaf bascule bridge. The first bridge was opened to traffic in 2001 and the second bridge will be opened in late 2002. The drive system comprises an enclosed differential reducer with two 100 hp d.c. motors on a common input shaft. Each motor is driven by a single, Allen-Bradley, regenerative SCR drive. The motors are sized to operate the leaf on a single motor. The drive system was designed, fabricated, and set up by a value added control contractor working directly for the drive manufacturer. The motor drives were set up and tuned in a single afternoon.

Operating the leaf on a single motor is, by far, the simplest solution. There is no synchronizing or load sharing headaches. The drive is adjusted to provide smooth acceleration, top speed is set, creep speed is set, deceleration is adjusted, and current limiting is set. A few test openings are conducted to adjust the slow down limit switches. Repeat the process for the second drive and set up is complete.

There may be a case in which the existing machinery and motors are not suitable for single motor operation due to the size of the input shaft. When both motors must be operated, load sharing is accomplished by operating both motors from a common source. In the case of d.c. motors, the motors would be connected in series so that each motor has the same current. In the case of a.c. motors, the motors are connected in parallel so that each motor has the same voltage and frequency. In either case, if the motors are of the same rating and manufacturer, they will provide as nearly equal torque as is possible.

- Wishkah Bridge in Aberdeen, WA was rehabilitated in 2001. It is a single leaf Strauss bascule with overhead counterweight and machinery. The leaf operating machinery comprised two wound rotor motors on the common input shaft of a differential reduction gear system. The wound rotor motor controls were resistors and control relays. The machinery and wound rotor motors were retained. The motor controls were replaced with two Hubbell SCR variable voltage motor controllers. The motors are connected in parallel to operate on a single drive with a single tach-generator feedback. The second drive is standby. A selector switch is used to transfer the motors from one drive to the other.

  Getting the system up and running was not without problems. But the problems had nothing to do with load sharing or speed control. Tuning the drives went quickly and, once tuned, the machinery operated smoothly and gently.

There are mechanical design considerations in using a single primary reducer that must be addressed. The single enclosed reducer is, by definition, a single point of failure. However, there are few, if any, cases of a primary reducer failure that allowed the bascule leaf to fall. If there is a failure of a coupling or a broken tooth on the pinion, the differential could counter rotate and allow the leaf to fall. This can be prevented by locating the machinery brakes on the output shaft of the reducer or building the differential to allow only one counter rotation of the output shafts. Locating the machinery brakes on the output shafts of the reducer will require the brakes to be larger but they can also be used to block one side and operate the leaf on a single rack.

Electronic Load Sharing

In the later bascule bridge designs, the machinery was separated with no mechanical connection between the two sides other than the bascule leaf itself. A motor-reduction gear set was located on each side of the bridge. Each side is mechanically independent of the other. The attraction of this design was that the amount of machinery was reduced and the leaf could be operated on a single motor-reducer set. This design is also the most difficult for the electrical engineers because synchronism and load sharing are their responsibility.

There were many different types of motor controllers used in these systems. Many were operated open loop. The motors were given equal voltage and they loaded up to what ever they needed to operate the machinery.

Since the mid 1980s, electronic motor controller manufacturers have aggressively marketed the concept of the "electronic line shaft" for operation of movable bridges. The technology has worked exceptionally well for high precision, multi-axis position control manufacturing. Paper mills, newspaper printing plants, and similar linear processes have had tremendous success with the electronic line shaft concept. These are liner processes that require variation of speed and torque of high inertia winding machinery while also maintaining linear synchronism of all the machines in the line.

One would think that torque and speed control for two motors operating in a single axis would be easily accomplished with equipment capable of such high precision. Based upon the brochures and application guides, it should be a simple master-slave configuration. Set the speeds, acceleration ramps, and current limiting and you are done.

The following cases demonstrate that on movable bridges, electronic torque sharing is a hit and miss kind of thing. Some applications have been more successful than others.

- University Bridge in Seattle, WA, was rehabilitated in 1988. Originally the bridge had two series wound d.c. motors connected to a common input shaft of the primary reduction machinery. The output of the primary reduction was a differential. The machinery was located behind the counterweight. Power was transmitted to the pinions via line shafts, bevel gears and secondary reducers.

  The replacement machinery is independent motors and reducers. The bridge has one of the most sophisticated regenerative, four-quadrant, SCR direct current drives that was available at the time; a Reliance DCS system. The drive controllers are dedicated programmable controllers (PLC) in a master-slave configuration. However, communications is a high speed, peer-to-peer link between the two PLCs.

  The drives were designed and built by a major electrical equipment manufacturer. They were also not the lowest bid. Because the factory was responsible for the integration and set up of the drives, the owner justified paying the higher price. The drives were installed and set up by the manufacturer's field engineer. With all of his training and experience, it still took about six weeks, full time, of trial and error adjustments before the owner accepted it. The bridge operates smoothly and quietly. Load sharing shifts from one motor to the other within a 60-40 % split.

- Chehalis River Bridge in Aberdeen, WA was partially rehabilitated in 1992. The original drive machinery was separated motor-reducers. The motors were shunt wound d.c. motors, connected in series to a motor-generator "Rototrol". The motor generators, for one half of the bridge, were replaced with two Saftronics regenerative, four quadrant, SCR drives. The original motor-reducers were retained. The integrated motor drive system was designed and fabricated by a value added control system contractor who purchased "off the shelf" drives chassis and components from at least four different manufacturers. The system was installed by the electrical contractor and set up initially by the control system contractor. After exhaustive trial and error adjustments, the drive manufacturer was called in. Eventually, the drive manufacturer modified the controls with a hand-soldered breadboard circuit. Load sharing is marginally effective as the load is shifted from primarily one motor to the other for the duration of the operation.

  To be fair, the bridge operates nice and smoothly. However, the owner has only sketchy documentation for the breadboard circuit and no instructions for how to replace it if it fails.

- First Avenue South (East) Bridge in Seattle, WA was rehabilitated in 1998. The original drive machinery was separate motor-reducers. The main motors were shunt wound d.c. motors, connected in series, to motor-generators, similar to the Chehalis Bridge. The motor generators were replaced with Baldor regenerative, four quadrant, SCR drives. The integrated motor drive systems were designed, fabricated, and set up by a value added controls contractor. The controls contractor was one of the most experienced movable bridge system contractors in the country. Experience not withstanding, the electrical contractor purchased the drives for them and required them to use a brand that they never used before.

  The balance on this bridge is such that the center of gravity goes over the top of the trunnion. The trunnions are also roller bearings. These two conditions probably contributed most to the drives not being able to stay in synchronism. The load shifts from being driven, to no load, to the load returning in the opposite direction.

  During the initial setup, the drives could be synchronized up to the point of balance. Because the leaf coasts over the top then free falls back onto the opposite side of the next teeth, tooth contact between the pinion and the rack was lost. The drive would immediately compensate to retard the load, and go into a hunting mode, with a lot of electrical groaning and mechanical clunking.

  After weeks of trial and error, the contractor called in a factory engineer. The factory engineer reassured the owner that the drives would load share as advertised and set about making changes here and there and suggesting other changes to the contractor. A resistor and capacitor circuit was added to introduce a ramp to the speed demand signal. The speed control circuit was revised from a resolver feedback loop to open loop control with armature voltage feedback. Firmware programming was changed. Yet, the system never did accomplish load sharing for the entire range of motion.

  On a positive note, the bridge operates smoothly and quietly. Prior to the installation of the new SCR drives, there was an audible clunk as the rack shifted from driving side of pinion tooth to the backside of the next. Now, the leaf operates primarily on one drive while the other lags slightly. The effect is that the leaf is snubbed between the two drives so that the rack teeth cannot lose contact with the pinion teeth. Although the drive is not load sharing, the groaning and clunking are gone and the operations people are happy with what they got.

- 17th Street Causeway Bridge in Ft Lauderdale, FL is a new four-leaf bascule bridge. It has independent motor-planetary gear reducers and roller bearing trunnions. The primary drive components are Baldor, the same as model as those used on the First Ave. South Bridge. The control system was fabricated and installed by a value added controls contractor using off the shelf drive chassis and other component parts. Again, there were countless iterations of adjustments. When the first bridge was put into service, the controls contractor was successful in getting the drives to operate smoothly, but not to load share. The second bridge was built during the following 18 months. During that time, the drive manufacturer sent factory engineers and technicians, repeatedly, to try different fixes. Most of the fixes that were tried on the First Avenue South Bridge were tried on 17th street. However, the resolver feedback loop was retained.

  The factory engineers were partially successful. By the time the bridge was formally dedicated, all four drive pairs could load share within a 60-40% range. It should be noted that the center of gravity on this bridge stays on the channel side of the trunnion.

There are many contributing factors to why the electronic drives are so difficult to set up. The dynamics of a movable bridge, especially a bascule leaf, are different from most of applications for which electronic drives were designed. In most manufacturing processes, the motor load is relatively constant. The drive vendors sometimes make reference to paper machines as a high inertia load comparable to a movable leaf. There is indeed a steady increase in torque but it at a low rate of change with few disturbances.

On a bascule leaf, the load changes continuously, but not at a constant rate, as the x-component of center of gravity moves toward or away from the trunnion. There are variable loads such as rain, ice and snow, and disturbances caused by gusty winds. Because the leaf is balanced, the leaf has a tendency to coast. The motor is constantly loading up and easing off. On some bridges, such as the First Avenue South Bridge, Chehalis River Bridge, and University Bridge, the center of gravity goes over the top of the trunnion so there is a period in which the load goes away, then returns in the opposite direction. Trunnions with frictionless roller bearings, such as those used on the First Avenue South and the 17th St. Causeway Bridges, compound the problem. Trunnion friction in this case is desirable because it provides, at least, a small amount of resistive force for the drive to work against. Without adequate resistive force, the rack and pinion teeth may lose contact. If the drive is set up to follow a speed profile, as tightly as most manufacturing motion control applications require, the drive will over compensate and induce a resonance into the leaf. The result is a very impressive, if somewhat frightening, erratic leaf motion and noises emanating from the machinery.

Now, consider how the master-slave connection between two drives works. Using feedback from the master motor, the master drive tries to maintain speed control of the leaf by varying the voltage, (speed), and current, (torque), to the master motor. At the same time, it is telling the slave drive to follow. In turn, the slave drive varies voltage and current to the slave motor. First, there is some delay between the time that the master calculates the speed error and adjusts the master motor voltage and current, then there is the time delay from when the slave receives the signal from the master and when it adjusts the slave motor voltage and current. This all happens within milliseconds. But, when just a few revolutions of the input shaft can mean the difference between the pinion being in contact with one tooth or another, a few milliseconds is not fast enough. If the master drive senses over speed and tries to retard the leaf, (reverse the motor) just as the slave drive has gotten the increase torque signal, the result is the leaf in a rocking motion, with the pinions slamming in opposite directions.

In all the example cases, the drives were made to operate the bridge smoothly. There were some wild operations in the initial trial runs. The first adjustments involve increasing the response time and reducing the gain so that the drives do not try to follow, too closely, the typical movable bridge trapezoidal speed curve. By manufacturing standards, the resulting speed control is so sloppy, it is virtually an open loop.

Adjusting the load sharing between the two motors is more complicated. By observing only the motor current readings on the drives, one could easily infer that the drives were sharing the load. This is because there is time lag between what is happening at the motor and the drive generating a usable signal to the digital panel meter. While the meter reading is changing, all kinds of changes are occurring in the pinion shaft. Regardless of how the motor currents compare or how smoothly the leaf appears to operate, measuring strain gauges attached to the pinion drive shafts and plotting the readings simultaneously for the operating bridge is the only way to tell how effective the load sharing is.

The typical strain gauge traces are sinusoidal as the shaft deflects with pinion to rack tooth engagement. On separate occasions, the initial results of strain gauge measurements were that the plot traces of the two strain gauges were mirror images of each other. Both times, the interpretation of the traces was that the polarity was reversed on one of the sensors. Closer examination revealed the rack was turning one pinion.

To a controls contractor, or vendor, who has previously used only motor currents as a means of measuring motor performance, this is a new and confounding dimension.

In a few cases, the motor drive manufacturers have succeeded in achieving an acceptable degree of load sharing. That is, the owner finally accepted it. In the end, the manufacturers have had to make product modifications and design changes in the field. There were fixes, in the form of a resistor and capacitor circuits added to the main control board or reconfiguration of tables in undocumented levels of the processor programming.

Hydraulic Load Sharing

Hydraulic load sharing requires the least amount of electrical speed control. Motor starters are required for the pumps and control wiring is required for the control valves. After that, speed control and load sharing is a matter of flow and pressure control valve adjustments. As long as the same flow and pressure is going to each of the hydraulic motors or cylinders, the load will be shared equally.

It is amazing just how complicated this can be. In Florida, over a ten year period, approximately sixteen Hopkins frame movable bridges were rehabilitated and six new bridges were built using hydraulic power. Roughly half of the bridges used hydraulic motors and half used cylinders. The same basic hydraulic schematic was provided in the contract plans for all of the bridges, but the ultimate design responsibility was the hydraulic control contractor's. The work was done by five contractors. Each had a different approach ranging from KISS to extreme. What one contractor could accomplish with a single proportional pressure relief valve, a single bi-directional proportional flow control valve, and a handful of relays took another contractor the same valves plus flow and pressure transducers, additional directional flow control valves and a dedicated PLC.

Conclusion

A movable bridge is a massive but simple integrated machine. There are many design solutions to movable bridge electrical-mechanical operating systems. The old designs that worked well, one hundred years ago, still work today. Load sharing between the pinions is a mechanical issue that is best left to the machinery designer. But, if the electrical engineer must solve mechanical problems, electronic drives can be made to work with some degree of success. Solid-state drives have proven to be a perfect replacement for simple motor speed control but not necessarily for load sharing.

The electronic line shaft concept needs more development for movable bridge applications before a clear advantage over the more traditional approaches can be demonstrated.

In all of the example cases, the drive manufacturer's expertise was required to get the systems up and running. Intimate knowledge of the drives circuitry and programming is of particular importance in a low bid environment in which third party contractors take on the responsibility of making the system work. Unless they have enough prior experience with the specific make and model in question or factory training, the controls contractors do not have the requisite knowledge, or budget, to develop and make the necessary changes to make the system operate as required. Excessive set up time is required. Product design changes are required. Contractor complaints about engineering errors and allegations of flawed design abound.

Of greater concern, is the owner's ability to maintain and repair the drive if something fails and it is necessary to replace a part. In the end, the owner may end up with a system that has "Do not touch" as the first maintenance instruction.

Biography

Rick Newcomb has nearly 30 years of electrical power and motor control experience. He graduated with a B.S. from University of Houston in 1973. The first 14 years of his career were in power and control design-build in the petrochemical industry. His hands on experience began when programming a PLC involved burning a chip and a variable frequency drive was set up with a voltmeter.

He has been involved, almost exclusively, in movable bridge power and control systems since 1986. He has designed new or replacement electrical power and control systems for 37 bridges. His experience, ranging from inspection to construction assistance and startup, includes more than 50 movable bridges.

He has been member of the Parsons Brinckerhoff Complex and Movable Bridge service center in Tampa, FL for 11 years. He lives in St. Petersburg, FL with his wife and teenage son on their ketch rigged sailing yacht. As a user of both highways and waterways, he has a personal interest in keeping movable bridges, movable.