HEAVY MOVABLE STRUCTURES, INC.
NINETEENTH BIENNIAL SYMPOSIUM

October 16-20, 2022

Bridge Control System Upgrade(s): Three bascule bridges in three years, lessons learned

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Abstract

The twenty-plus year aged Allen Bradley control systems used by the four movable bridges maintained by Multnomah County were upgraded in the last three years for three bridges. These three bridges are double bascule types, which range from sixty to one hundred years in age, have an average bascule length of 130 feet, bascule assembly weight ranging from 4 to 5 million pounds, and use pairs of 75 to 100 horsepower 600 rpm ac motors to operate via open gear sets. The general upgrade approach for each of these bridges involved purchasing new Allen Bradley/Rockwell Automation motor drives, touch screen operator input panels, plc processors, digital and analog input/output cards, plc and touchscreen programming software, industrial managed switches, miscellaneous relays and electrical components. These replacement components were assembled and networked (Ethernet protocol) for bench testing at the county bridge shop to developing and test the programming and hardware configuration prior to installation at the bridge. County Maintenance and Engineering worked together to prepare and plan for installing the upgraded control system. Generally, installation occurred over a two-week single bascule operation closure period for each bascule of the double bascule bridges. Upon completion of the hardware installation, a Rockwell Automation motor drive consultant was contracted to work with County personnel to commission each pair of motor drives on the upgraded bascule over a two-day period. Open loop vector control scheme with encoder speed feedback was used for the three bascule bridges. This provided adequate startup torque and did not require fine tuning drive parameters for load sharing between the motor pairs. Initial opening and seating of the bascule bridges required plc programming modifications to account for machinery gear set shaft residual torsion (wind up), and drive parameter torque limit modifications during the bridge seating process. Challenges during bascule operation motor drive commissioning include unexpected bascule imbalance, motor brake timing relative to motor shut off, machinery shaft residual torsion, motor drive output high amperage spikes to maintain zero speed.

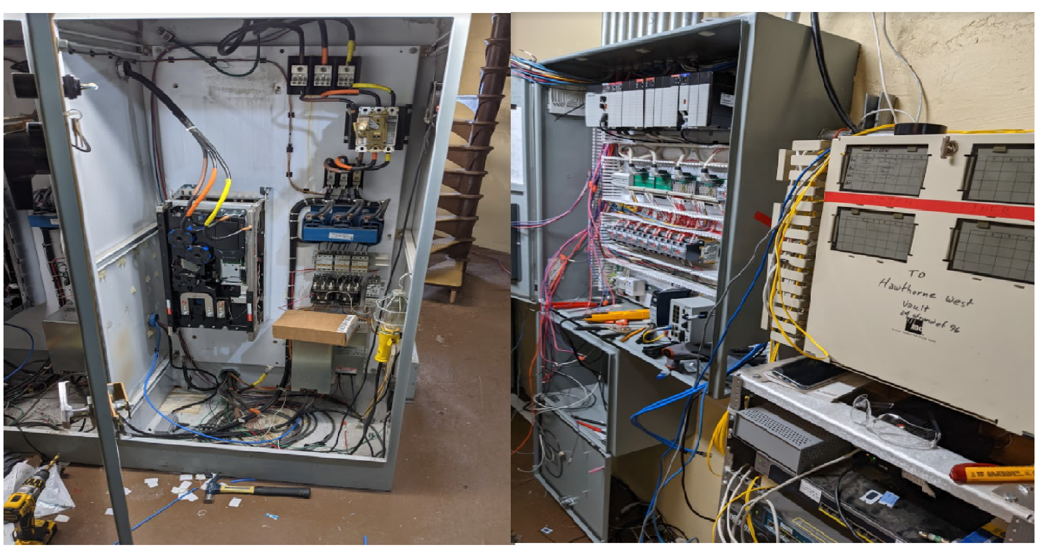


Figure 1 Burnside Bridge Control System Upgrade: motor drive, plc cabinets during construction. The bridge optical fiber PLC network termination box is located on the far right. The yellow optical fiber cable can be seen plugged into the industrial network switch on the bottom row of the PLC enclosure cabinet.

Control System Upgrade Scope:

Replace the current 480V Allen Bradley 1336 AC drives, SLC5/05 controllers plus associated input/output cards with the 480V Allen Bradley 750 series AC drives, Allen Bradley ControlLogix L80 series controllers plus associated input/output cards. Replace the Allen Bradley 12" touch screen PanelView 1000 with an Allen Bradley 15" PanelView Plus 7 Performance touch screen. Replace all optical fiber media converter communication network modules with industrial Allen Bradley Stratix 5700 switches. Use existing electrical cabinets for the replacement drives and PLC systems, by replacing the backplanes only, and upgrading the ventilation fans. Upgrade relays, fuses, and terminal blocks in the cabinets.

Convert the existing SLC5/05 controller programming in Rockwell Automation RSLogix 500 to programming in Studio 5000 Design Logix for the ControlLogix L80 series controllers. Convert the existing PanelView 1000 PanelBuilder 32 programming for PanelView Plus 7 Performance programming in FactoryTalk View Studio Machine Edition. Programming tasks are to improve the existing logic for safety, control, maintenance, reliability, and security.

Operation of a movable bridge span:

Bridge control systems upgraded were for three double bascule bridges, and currently in design stage for one vertical lift bridge. Each bascule has a dedicated controller, two motor drives-each driving a motor, one bridge operator input touch screen; thus, each bascule bridge has a total of two controllers, four motor drives, and two touchscreens. Typical bridge movable span operation motor control consists of ten selectable operation speeds with slow down speeds and brake control that are automated during approach of final closed and opened positions. Both bascules on a double bascule bridge are usually controlled from a single control room, made possible due to each individual bascule controller being programmed to communicate with each other over a dedicated optical fiber control network, constantly updating the status of the bridge operation safety interlocks and motorized devices. The bridge operator touch screen control consists of approximately six to seven sequential operating screens (see Figure 2), allowing an operator to control various stages of safety interlocks prior to setting the movable bridge span in motion. These safety interlocks typically include traffic light control, traffic and pedestrian gates, machinery and motor brakes, bridge moveable span locks. Operation status of the safety interlocks and movement of motorized devices, such as gates, are graphically depicted on the respective operation display providing feedback and control input options to the bridge operator.

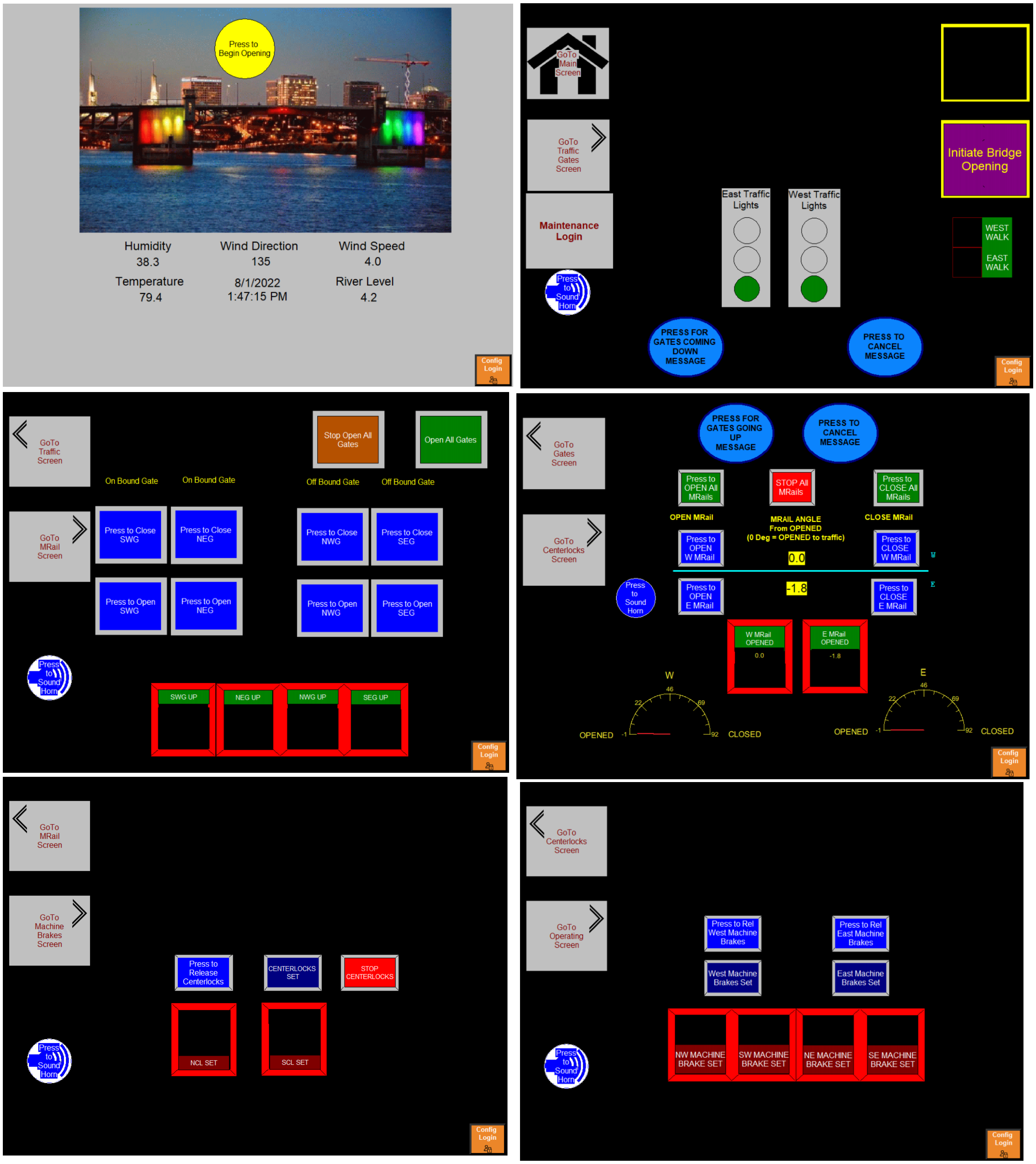
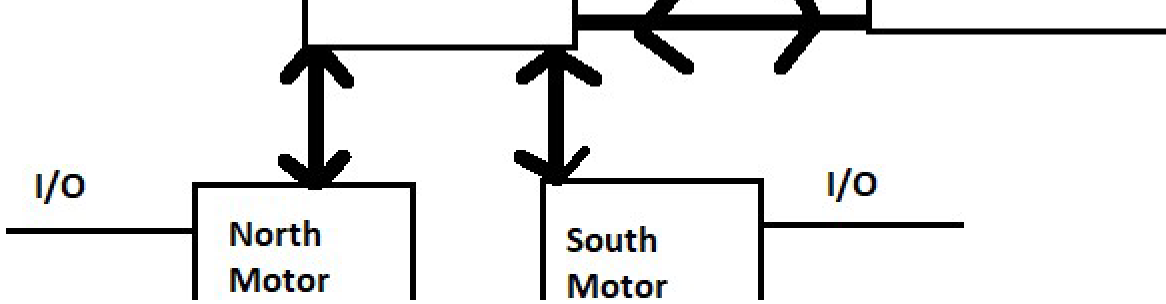

Press to Begin Opening
Humidity
38.3
Wind Direction
135
Wind Speed
4.0
Temperature
79.4
8/1/2022
1:47:15 PM
River Level
4.2
Config Login
GoTo Main Screen
GoTo Traffic Gates Screen
Maintenance Login
Press to Sound Horn
East Traffic Lights
West Traffic Lights
Initiate Bridge Opening
WEST WALK
EAST WALK
PRESS FOR GATES COMING DOWN MESSAGE
PRESS TO CANCEL MESSAGE
GoTo Traffic Screen
GoTo MRail Screen
Stop Open All Gates
Open All Gates
On Bound Gate
Off Bound Gate
Press to Close SWG
Press to Close NEG
Press to Close NWG
Press to Close SEG
Press to Open SWG
Press to Open NEG
Press to Open NWG
Press to Open SEG
SWG UP
NEG UP
NWG UP
SEG UP
GoTo Gates Screen
GoTo Centerlocks Screen
PRESS FOR GATES GOING UP MESSAGE
Press to OPEN All MRails
STOP All MRails
Press to CLOSE All MRails
OPEN MRail
MRAIL ANGLE From OPENED (0 Deg = OPENED to traffic)
CLOSE MRail
Press to OPEN W MRail
Press to CLOSE W MRail
0.0
-1.8
Press to OPEN E MRail
Press to CLOSE E MRail
W MRail OPENED
E MRail OPENED
W
E
OPENED
CLOSED
GoTo MRail Screen
GoTo Machine Brakes Screen
Press to Release Centerlocks
CENTERLOCKS SET
STOP CENTERLOCKS
NCL SET
SCL SET
GoTo Centerlocks Screen
GoTo Operating Screen
Press to Rel West Machine Brakes
Press to Rel East Machine Brakes
West Machine Brakes Set
East Machine Brakes Set
NW MACHINE BRAKE SET
SW MACHINE BRAKE SET
NE MACHINE BRAKE SET
SE MACHINE BRAKE SET

Figure 2 Typical bridge Operations screens



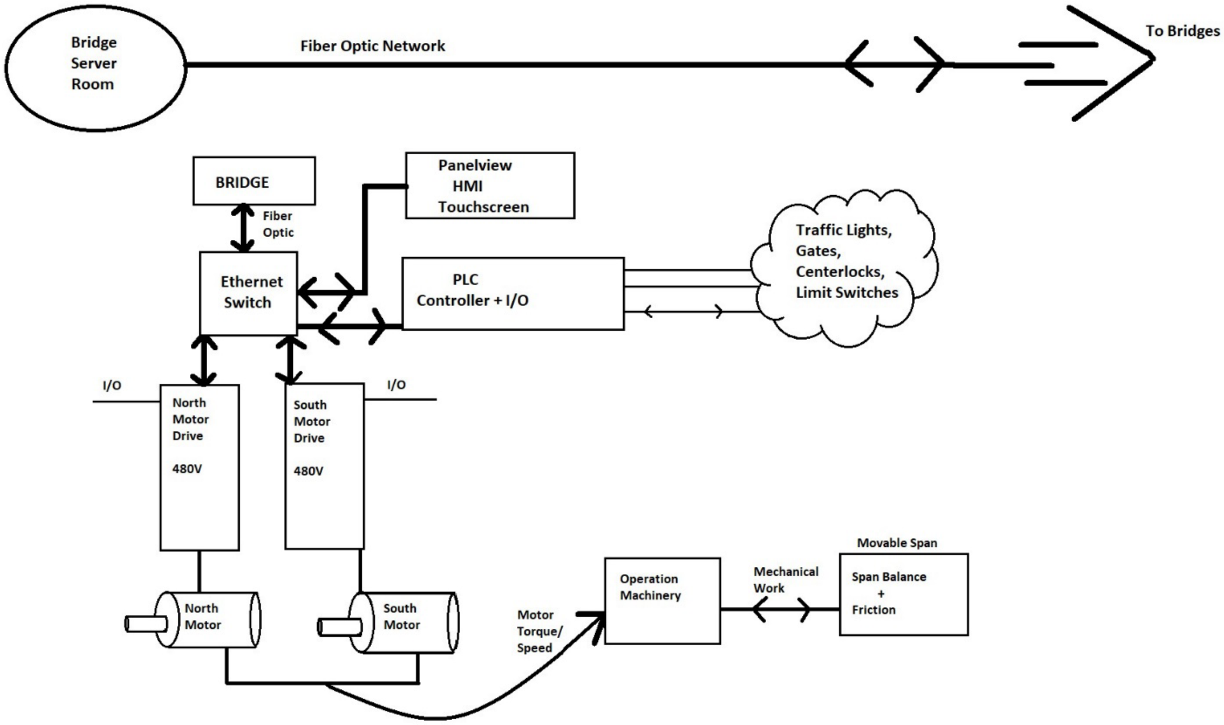


Figure 3 County bridge control system overview configured with star network topology.

All bridge programable logic controllers (PLC) are networked to each other over the plc network via a central distribution network switch to each of the local bridge industrial network switches using ethernet communication protocol. From the local bridge industrial switch, copper ethernet cable connects to the local bridge control hardware: Touchscreen HMI, PLC Controller, a pair of motor drives. The current optical fiber network, and local bridge network topology are both star network configured, which does not have any automated alternative communication path redundancy. There are multiple backup optical fibers available to each local bridge industrial network switch, as well as spare control system parts to provide an acceptable level (cost/benefit perspective) of minimizing system downtime. Inherent redundant network topologies exist such as ring or mesh networks, but these network topologies are currently not within our budget. There is already more than a mile of optical fiber used. Network security threats are also an ongoing concern, and require diligent firmware and software update maintenance, as well as best practices for the network infrastructure from a security perspective.

Typical double bascule bridge control system upgrade stages performed:

1. Procure control system upgrade components: PLC system with capacity for Input/Output expansion (New networked/smart sensors are increasingly available, and more sensors are being used for preventive maintenance improvements) The control system parts cost for a double bascule bridge were roughly $80K to $120K. These parts generally included two PLC systems, two HMI touchscreens, four motor drives. No modifications were made to the motors. All the

bascules have more modern induction 'inverter duty' motors (able to withstand the high microsecond duration voltage spikes inherent in variable frequency drive (vfd) controlled motors), except the Morrison bridge. The Morrison bridge has very large framed, General Electric, twelve pole, 100hp, induction motors, not designed for vfd's, but robust. Motor replacement is planned for action soon on the Morrison. We had to rebuild one of the motors due to winding insulation failure about two years after the control system upgrade. The motor was rebuilt to inverter duty specifications (more resistant to variable frequency drive high voltage spikes breaking down winding insulation). The cost of the rebuild resulted in a cost about 66% the cost of a new replacement motor. The rebuild took a month longer than normal because the windings used formed copper wire, which had to be ordered. Rectangular 'formed' wire allows tighter packing than round wire, providing a higher power density winding, a feature used in higher quality wound motors. The Morrison bascule is capable of operating with one motor, so this offers some operational flexibility.

2. All the County bridge operation deviations effecting river navigation require Coast Guard approval, typically a ninety-day approval process. The construction schedule, and minimization of road and river traffic deviations were planned. The construction stage of the double bascule control system upgrades typically took two to four weeks per bascule; thus, single leaf operation was implemented while each bascule was under construction. Total bridge closures were limited to two days per bascule, except the Broadway bridge, which required a three-day closure per bascule, due to two additional motor drives per leaf (for 600V electric Streetcar overhead catenary disconnect system). Tugboat assist, upon ship pilot request, was required during single leaf operation mode. Insurance covering bridge collision damage for the tugboat contract has been somewhat difficult to negotiate.

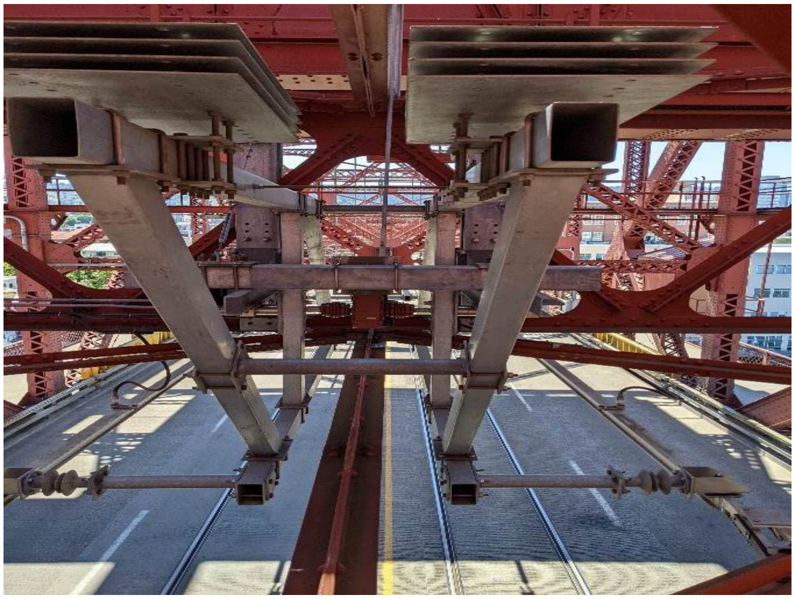
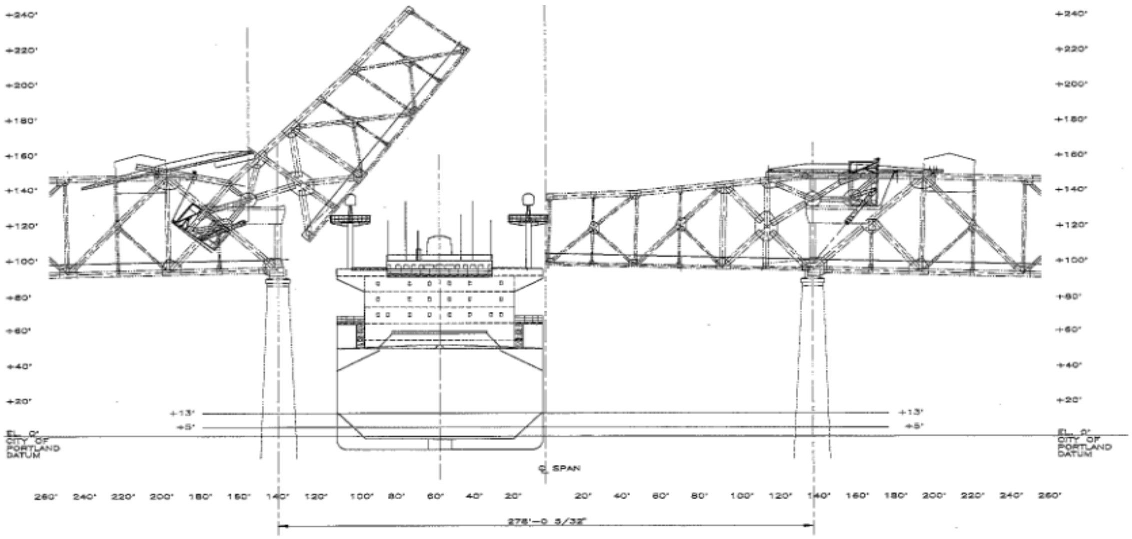


Figure 4 Broadway Bridge Streetcar OCS disconnect is a mini bascule device, controlled by a small 2hp motor drive, that rotates a section of the streetcar high voltage rails out of the way of the bascule counterweight for a bridge opening. There are two of these OCS disconnects per bascule.



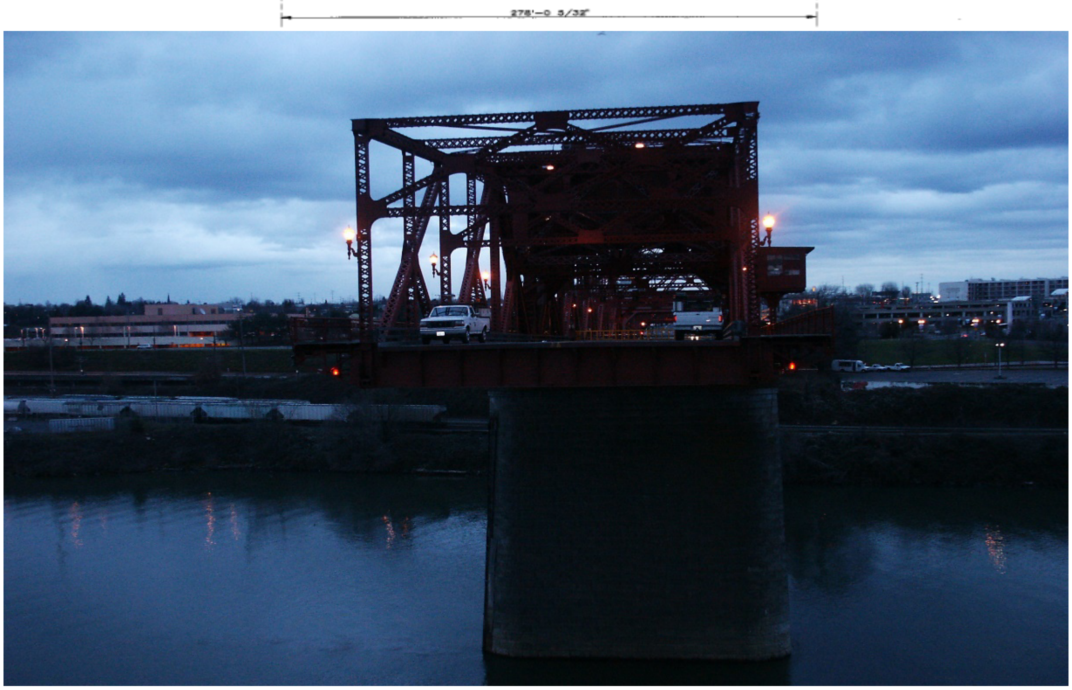


Figure 5 Broadway Bridge Single Leaf Operation, looking east. Large grain ships pass through this bridge during grain shipping season, and the fines for delaying a cargo ship like that are very high due to their tight schedule.

3. Once the parts were received, the County Electricians (Fred and Tracy) built the replacement PLC system on new back planes (with same footprint), that would be swapped with the old hardware mounted backplanes in the old electrical enclosure. Shown in figure 6: Top row is PLC rack empty of processor and I/O modules, Second row is terminal blocks to connect bridge operation PLC I/O modules to bridge operation devices such as traffic lights, limit switches, traffic gate motors, etc.., Third row is contact relays and fuse blocks, Forth row is a 24 volt power supply, power terminal blocks, industrial ethernet switch with copper wire ethernet ports for local bridge control device connection plus two optical fiber ports to connect to bridge PLC optical fiber network. Forced ventilation fans were upgraded on the enclosures for improved thermal management.

4. The Electricians built a switch board to emulate operation machinery limit switches, sensor positions, and traffic lights. Figure 7 shows the built switch panel with pivotable inclinometers, mounted on top, to emulate bascule angular position. The inclinometer sensor provides bascule angular position data within 0.01-degree resolution, which is used for position data in much of the plc program logic of the bascule bridge operation. Many engineering hours were spent here to test and debug plc and touchscreen

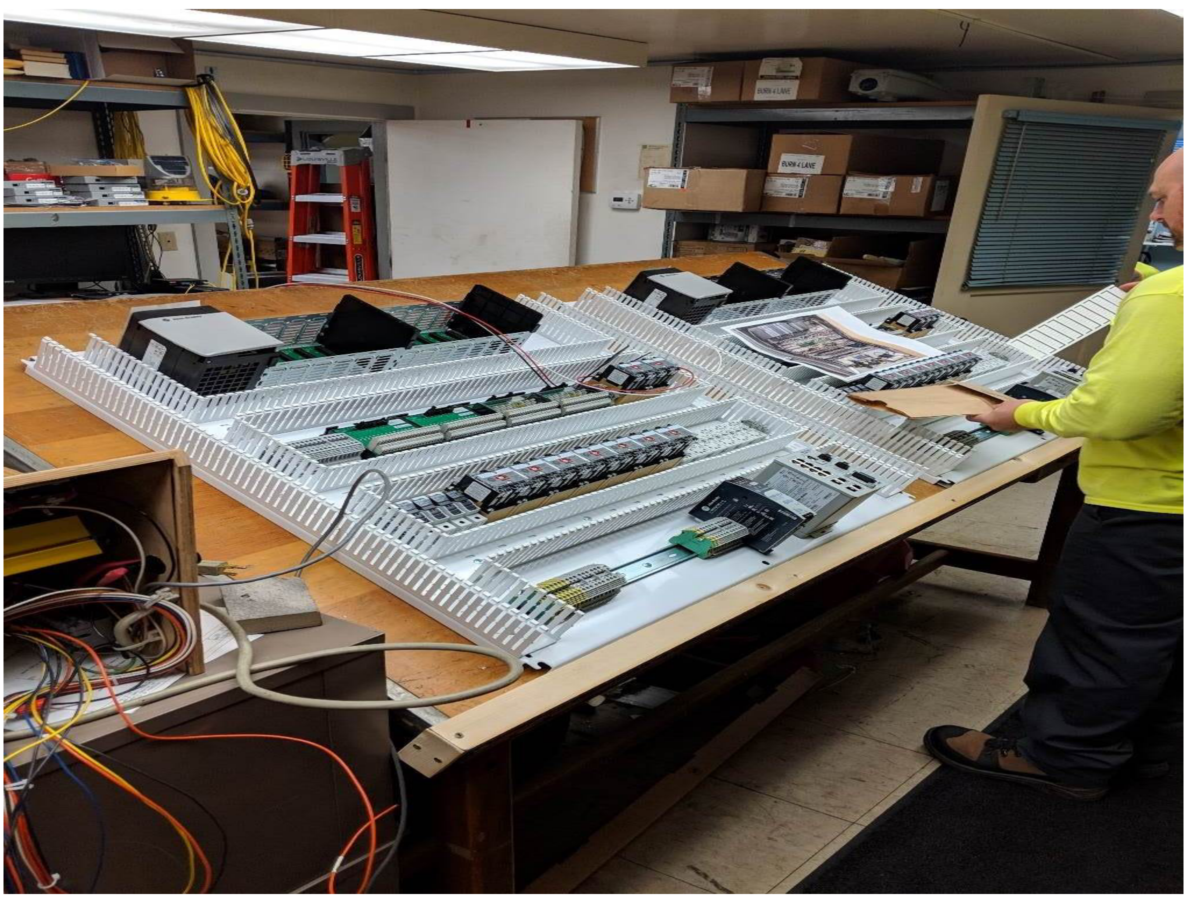


Figure 6 Multnomah County Electrician, Tracy, building in the bridge shop electrical room a pair of new PLC systems on replacement backplanes.

programming. This test bench system was setup to be remotely accessible, to allow work from the office, or a remote site. Access was limited to specific PC's, requiring two factor authentication login via virtual private network, through the County network to the PLC network. Generator powered motor drive testing was not remote capable. In the final stages of programming edits, Operations personnel were requested to use the HMI touch screens and provide feedback on touchscreen control graphics, as well as experience operation procedure training.

Figure 7 Emulation switch board, HMI touch screens, usb keyboards for touchscreen configuration input. In the background are a pair of plc systems in enclosures with drive communications ethernet cables tied to the post.

5. Setup the control system in the bridge shop to test: HMI touchscreen programming, PLC programming, motor drive programming, motor drive response. The 480V motor drives required use of a very loud portable diesel generator to power them, when the motor control commands had to be tested. A pair of small gearbox motors, for a future span lock upgrade project, were used to test speed and rotation direction commands input via the HMI touchscreen.

Figure 8 480V ac powered new motor drives at bridge shop, connected to gearbox motors in foreground for motor control testing of speed and rotation direction commands. Encoder setup and motor control testing was performed on the red gear motor system in the background used for the Broadway Bridge streetcar 600V overhead catenary disconnect system.

Figure 9 A very loud, 480V, diesel generator, used to power the motor drives in the shop to test motor drive/motor response. Generally, testing and troubleshooting motor drive setup and motor response required about 16 hours of generator operation.

6. Before starting construction, the bascule span balance should be checked by performing a drift test (coasting of leaf while it has some momentum to see how it coasts going up, and coasts going down). Wind loads will skew a drift test. Strain gauge readings from machinery shafts can also be used to ‘calculate’ the span balance necessary for available braking capacity with expected external bascule span loads such a wind, snow, and ice. Excessive bascule imbalance can be managed during motor drive commissioning, but it must be well within the braking capacity of the machinery without motor control, incase the motors are not being controlled correctly. County bridge control motor and operating machinery brakes will default to brakes set if the motor or motor drives lose power, or there is a loss in motor drive command communication. Next to the bridge control HMI touch screen, is an emergency stop button, which will stop all motors in the bridge operation system when these motors are controlled via the plc system. During motor drive commissioning, it is possible to bypass the plc system to control the motors, thus, it becomes essential to have a method for quickly cutting the power to the motor drives and/or motors, in case of motor control loss.

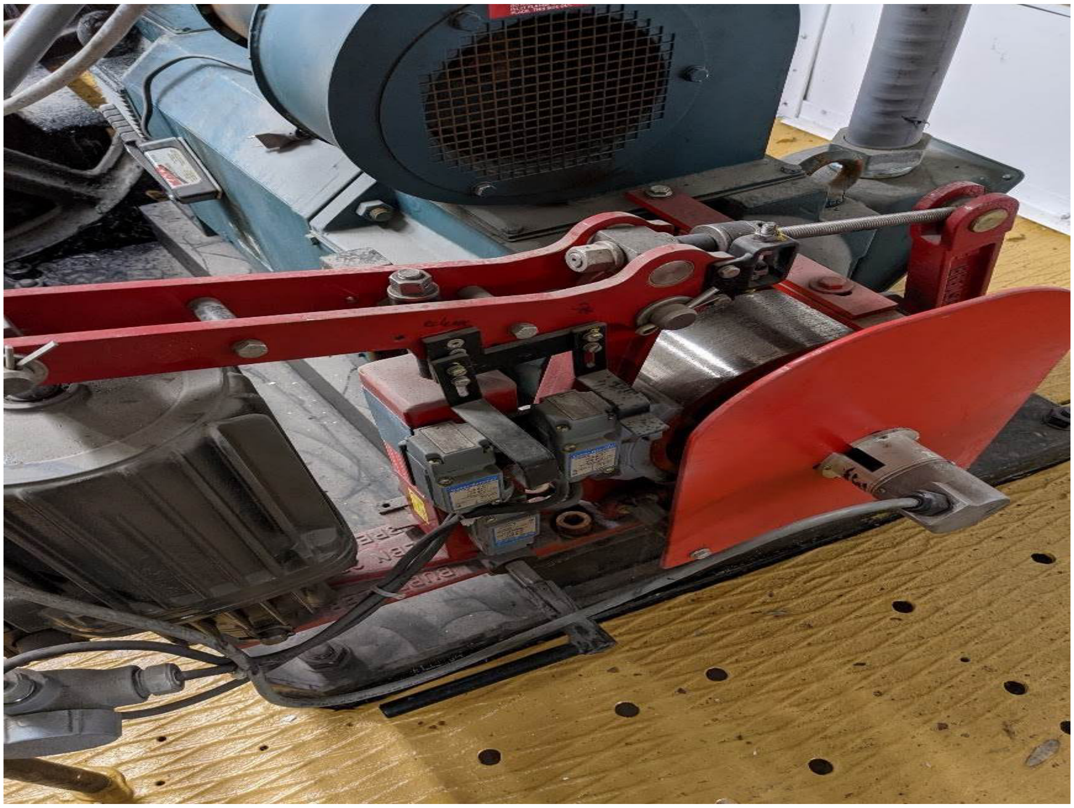


Figure 10 Burnside bridge, German made, motor drum brake. Limit switches indicate if the brake is released or set, and whether the brake has been manually released with the hand lever. Shown in the lower left quadrant of the image, the finned electro-hydraulic actuator actuates its full stroke within a fraction of a second.

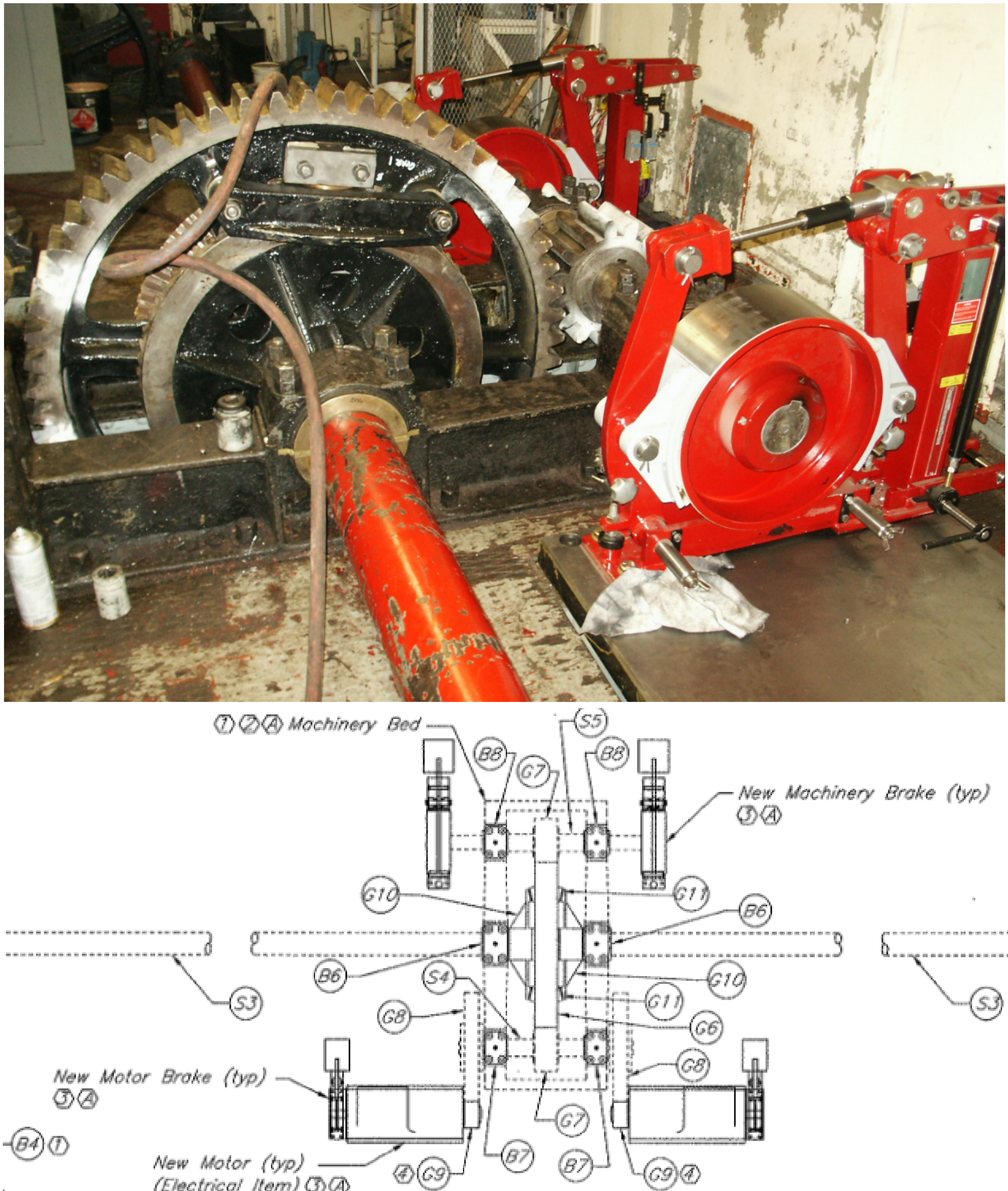


Figure 11 Burnside machinery brakes, located on other side of the central differential spur gear relative to the previously shown motor brake. The sketch above shows a motor brake for each motor and two machinery brakes that share a common shaft. Each of the County bascule bridge leaf's use dual electric motors, which share a common shaft drive open gear machinery (Broadway and Burnside), or share a common structure (Morrison motors structurally linked 58 ft apart, each driving a machinery set of open gears, which then drive a rack gear mounted respectively to the north and south bascule trusses.

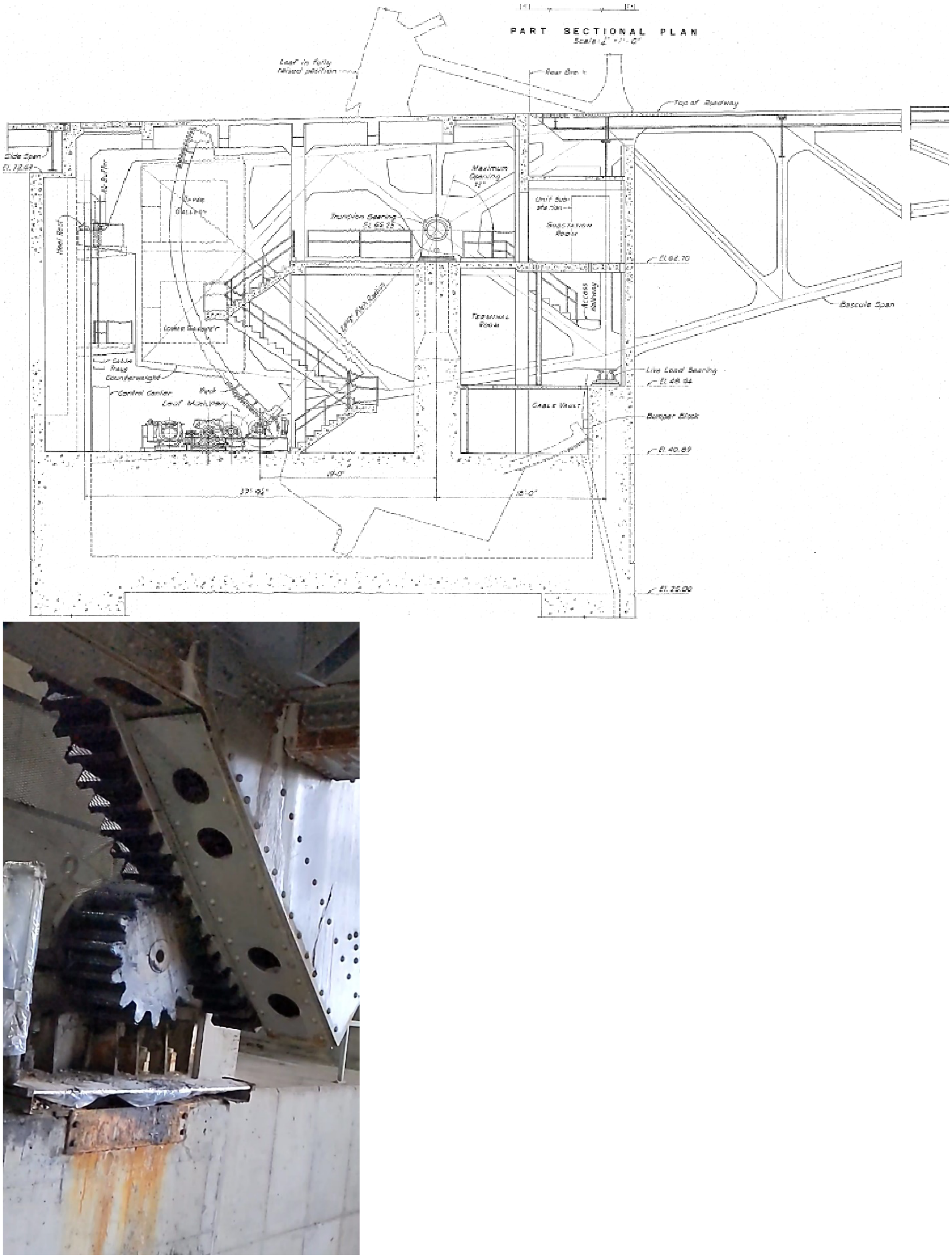


Figure 12 Morrison bascule is driven by a pinion/rack assembly on the north and south truss, 58 ft apart each other, of the bascule with the bascule structure acting as mechanical link between the two motor gear sets.

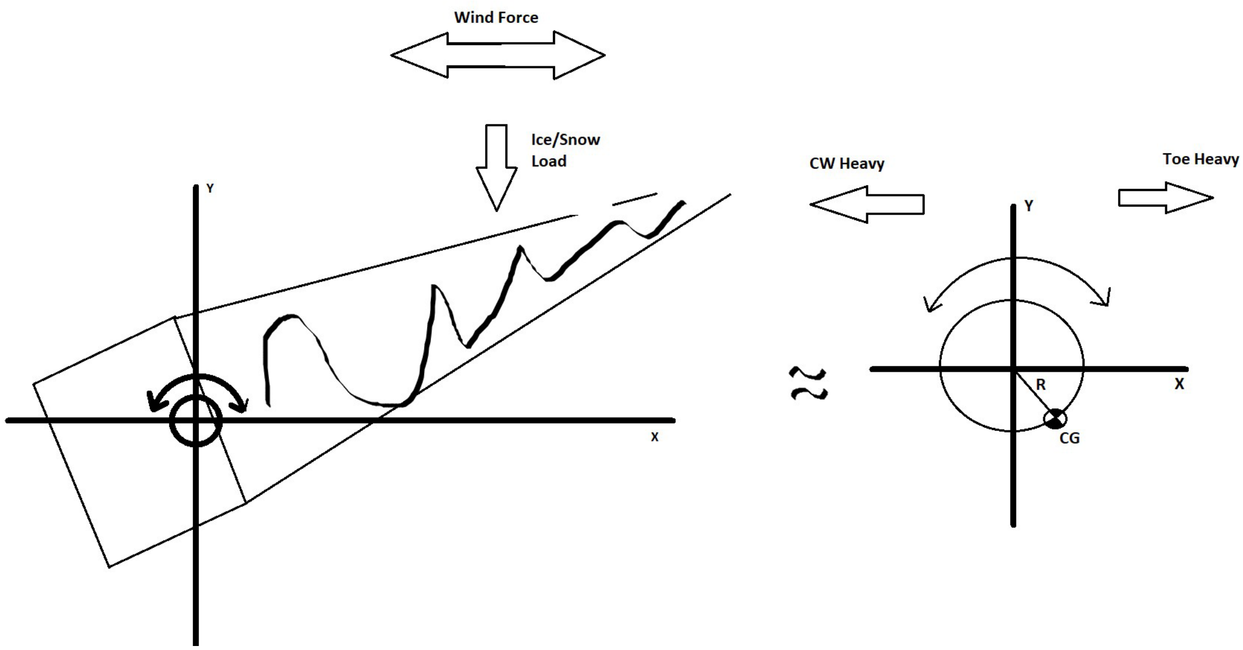


Figure 13 Span Balance. For a simple bascule, the system center of gravity, CG, is typically within inches, R, of the center of rotation. The CG induced torque of this bascule from closed to full open positions will vary as a sinusoidal function, since it moves in a circular path about the center of rotation.

7. Commissioning of motor drives were performed with an expert drive consultant. The motor drives are programmed micro controllers to control the voltage and current sent to the motor, and the phase difference between the voltage and current waveforms to create desired speed and torque performance. The motor drive parameters are tailored to the type of motor and its unique physical characteristics such as system impedance, inertia, magnetic characteristics. A weekend was allotted for commissioning of each bascule. This generally involved about two eight-hour days, and cost about $7K in consultant fees. The bridge was closed to road and river traffic to perform multiple test lifts and traffic control system tests (when control is in doubt, best be safe rather than sorry). All the bascule bridge upgrades utilized existing external dynamic brake resistor banks. The dynamic brakes are used to discard (in the form of heat via the resister banks) excess electrical energy beyond a threshold designed from motor drive/motor system electrical load limits, in order to decelerate the bascule to a given speed setting setpoint. The dynamic brakes are sized for the motor drive electrical capacity. Controlling the bridge speed deceleration load with the motor is like an electric vehicle, (ev) using regenerative braking. The ev motor slows down the ev and dumps the excess electrical energy back into the battery. All the County bascule bridges are balanced well, and the deceleration loads are rarely high enough to use the dynamic brakes when operating under normal circumstances, i.e., dual motors, no external loads such as wind, snow, ice. The commissioning typically starts off with inputting motor drive parameters based on the motor configuration, dynamic brake configuration, and type of motor drive. If there are feedback sensors for motor rpm and/or position, then additional drive configuration settings are included. An automated drive parameter (our motor drives have up to a thousand parameters) configuration procedure called 'Autotune' is performed. The most thorough autotune option is the dynamic autotune, where the motor is operated without a load applied, i.e., disconnecting it from the machinery. Instead, we used the static autotune option (no motor

rotation required), which provided satisfactory drive parameter settings for the motor control scheme we used (Sensorless-Vector mode). Static autotune takes a few seconds and does not require uncoupling the motor output shaft from the bridge operating machinery. Once all the drive parameters are checked, the motor is briefly energized to determine which way it rotates based on the command logic programmed in the new plc program. Starting and stopping using the plc generated motor drive commands are checked, followed by various motor speed settings and bascule response. Once the bascule can be speed controlled and stopped, the approach to the full open and full closed positions are tested for correct plc programmed automated slow down speeds, final position accuracy, motor peak loads, and the equalization of dual motor load sharing. Given all the County bridges use dual motors that share a common mechanical link, the motors must operate in sync with each other, i.e., their speeds must match. Additionally, each motor should share the same load, i.e., provide the same torque output. During commissioning, the parameters can be graphically monitored to compare how well the speed and torque match. The beauty of an ethernet connected drive is an engineer can remotely access the motor drives to monitor any number of drive parameters to see how the control system is operating. Motor drive output current was very useful to monitor how hard the motor is working, and what loads are occurring during bascule operation.

Figure 14 Fred, Mike, and Curt removing the old Broadway bridge motor drive. The external dynamic brake resister bank is on top of the motor drive electrical enclosure.

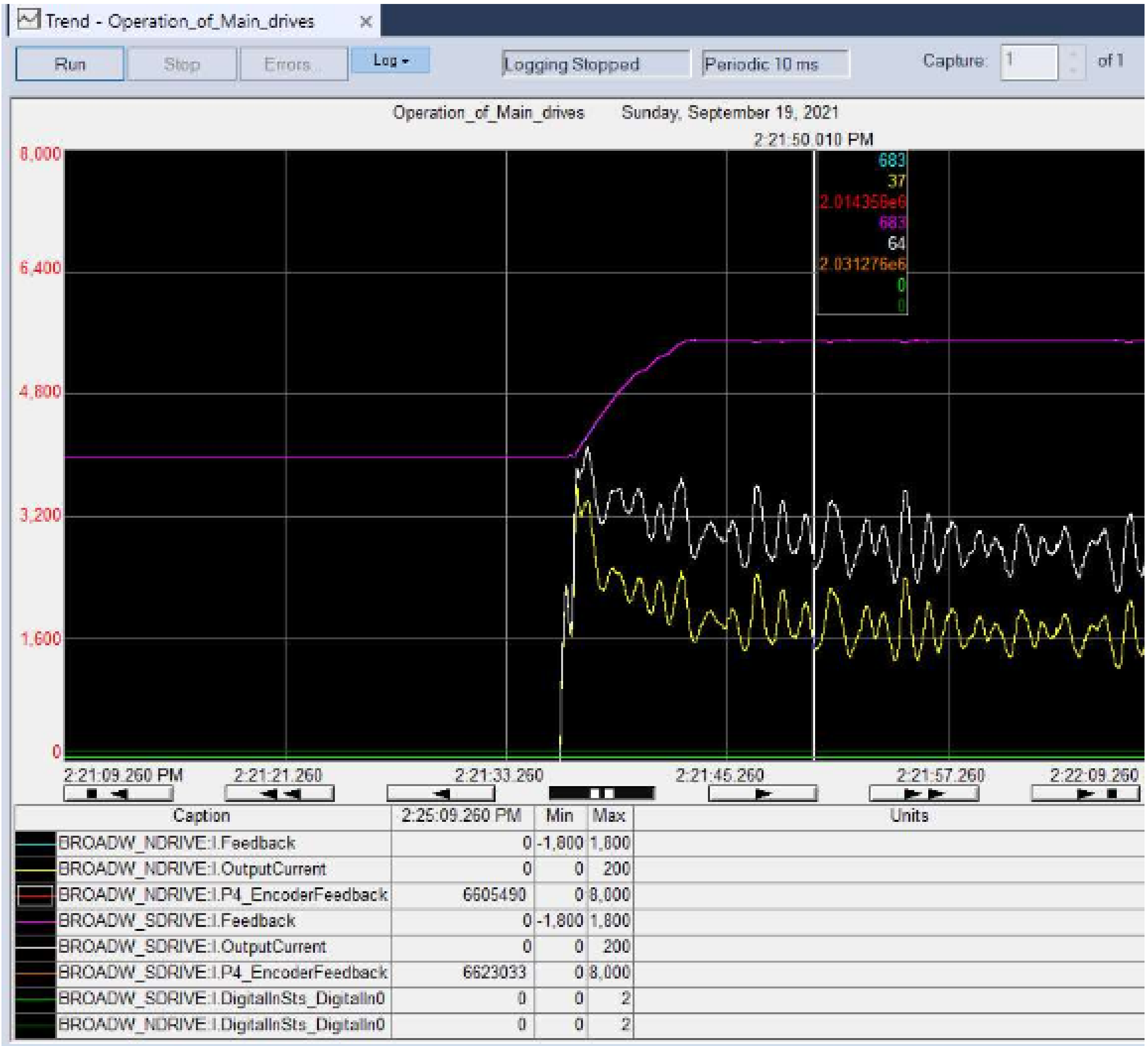


Figure 15 One of many drive commissioning plots monitoring north vs south motor current, motor speed selection, speed feedback value. In this case there is a 27 amp difference between the N and S 75hp motors that share a common shaft, each motor outputs through a gear reduction box to this common shaft. It is believed the south gear reduction box may be contributing a lot of friction.

Lessons Learned:

1. The Rockwell automated conversion program for the PLC programing and PanelView programing saved much time but will require significant editing due to hardware changes. It will create placeholders for addresses that involve hardware changes from the old system to the new system. These will often require corrections to eliminate program errors prior to being able to download to the upgraded processor and/or PanelView.
2. Using control system software real time graphical plots of events during test operation such as motor drive output current, brake actuation, motor speed, encoder counts, is helpful in troubleshooting program bugs, and evaluating acceptable operation.
3. The HMI control system touchscreen with authorized access maintenance screens proved useful in permitting authorized personnel to change constants used in motor control logic needing a qualified person to edit plc programming.
4. Use of visual indicators and alarm banners in PanelView programming has been helpful in providing feedback to bridge operators for motor drive status conditions and safety interlock troubleshooting. Expanding the amount of information to troubleshoot bridge control programs is planned to be integrated into PanelView displays.
5. Email and text messaging, to qualified Bridge Shop personnel, motor drive status and other plc program alarm status is planned but has not been easy to find applicable literature sources.
6. Testing motor drive behavior from plc programming is cumbersome due to 480V power being only available from generator power. Plc program testing with a switch board simulating limit switches was useful, as well as using 'forces' in the program. Actual input signal to input cards, however, could not be tested, and have sometimes resulted in time consuming field installed troubleshooting/test iterations. Emulation software may be useful for testing signal input response. Emulation of a motor drive is not known to be available but would be an excellent plc program testing tool.
7. Bridge seating motor and brake control was found to be unique for each bascule bridge due to the machinery/brake equipment. The following bullets summarize the uniqueness of controlling each bridge seating process.

- Broadway has only air actuated machinery brakes, which are relatively slow actuating compared to the electro/hydraulic actuators on the other bridge. The limit switches that indicate when the N and S Broadway machinery brakes are set had up to a 4 second differential, plus a long actuation time of almost 10 seconds from initiation of brake setting. This long period of time was too long to keep the span drive motor driving the bridge down into the seats and would overload the drives, potentially blowing a fuse. To solve this, the motor overcurrent-limit-parameter during the seating process was programmed to be changed from 187 amps to 80 amps. Once the earliest of the two brake limit switches indicated it was set, the motor reference speed was changed from speed 1 to speed zero and the overcurrent-limit-parameter was reset to 187 amps.
- During Broadway seating, the machinery shaft would sometimes unwind from accumulated torsion, after setting the speed reference to zero, combined with not enough machinery brake holding power at that moment. The unwind would cause the motor to rotate and create a 'back EMF' spike. This spike is believed to be the motor drive attempting to maintain zero speed by opposing the back EMF. Maintaining the 80-amp overcurrent limit parameter setting for the duration of the machinery shaft unwind limits the amperage magnitude of the drive response. Since the brake actuation time is too slow, and not fixable now, a delay timer was programmed to

delay resetting the overcurrent limit back to 187 amps. This reduced the back EMF spike that potentially could exceed the max allowable drive amperage.

- Broadway streetcar OCS motor drive control required increasing the existing programmed highest speed of the blue OCS to eliminate a hesitating motion behavior--probably due to a friction and momentum relationship. Increasing the blue OCS momentum created more of an impact force on the red OCS system during the closing process. Red always closes first, then blue closes and lightly impacts red during the last second of closing. This changes the final position of both blue and red, which is displayed in tenths of a degree on the touchscreen; however, the encoder counts 32768 pulses per revolution of the red and blue center of rotation axis, which equate to approximately one hundredth of a degree resolution. The upper and lower limits of the closed final position are programmed for each red and blue to allow for the variation in closed position. Changes in speed, or slow down speed set points will change the impact response and may require adjusting the allowable range of final stopped position. Streetcar said they can deviate a whole 4 degrees from horizontal, but this has not been demonstrated to the County. Current variation of final closed position does not deviate more than 0.2 degrees. There are no brakes holding the position of the OCS system, just gearbox friction. Bridge vibration may vibrate the OCS out of allowable position range, resulting in a safety interlock over limit that will currently lockout bridge operation of other safety interlocks. If vibration/position (not sure if it is currently trending) creep is trending problem, an out of position alarm can be programmed, and a special operation safety interlock bypass will have to be programmed, or the program changed to allow for operation with an allowable deviation from the closed position. We created a maintenance access screen Streetcar can use to adjust the setpoints and speeds if needed.

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Figure 16 Streetcar OCS maintenance screen.

- The pair of west bascule Broadway span drive motor currents often have a significant difference in operating motor current, indicating the load sharing is not evenly distributed. Encoder speed feedback in V/Hz control mode seems to help reduce the motor current difference (pair of motors share a common shaft), by the improved speed control. It was recommended to change the control method to Vector control, but not enough time was available to test this configuration. Vector control should greatly improve load sharing, thus minimizing the difference in motor current between the pair of motors sharing the same output shaft. The west motor amperage difference should be monitored to evaluate the long-term reliability of the motors.
- Initial opening operating machinery response of the Burnside bridge (from closed position) includes a residual machinery shaft torsion unwinding event when the machinery and motor brakes are released. The unwind motion is opposite to the shaft rotation for opening (similar to the Broadway seating response). This counter-rotation event will cause a 'decel inhibit' error in one of the motor drives. To eliminate this problem, a five second delay timer precedes the first speed reference input from the bridge operator, when opening the bridge from the closed position. The timer duration is set to delay motor drive speed input until the machinery unwind-event after brake release has stopped. It should be noted that the residual machinery torsion in the closed position is a result of the brake timing and applied span drive motor torque during the seating process. The seating process could be refined to reduce the residual machinery shaft torsion. The ideal seating process is to ensure the bridge live load shoes are in contact with the seats, and all gear backlash is 'taken-up' with minimal gear tooth contact loading on all the drivetrain gears while in the closing rotation direction. This ideal seating status ensures brake locked machinery will keep the bridge from bouncing up from road traffic vibration. The lift span imbalance should also ensure the span will not bounce up from road traffic vibration; however, the ideal seating status is an extra safety practice.
- The Morrison bridge also has a minor amount of machinery unwind during the initial opening process, but it has not been causing drive faults recently, due to reducing the residual torsion accumulated during the seating process. A delay timer will be introduced in the future, like the Burnside opening delay timer, to ensure seating torsion changes will not result in a span drive error during opening. The encoder arithmetic sign of the encoder and motor reference speed are not reading positive for opening and negative for closing, like the Burnside is currently configured. This will be corrected in the future for consistency in motor drive parameter configuration.
- Hawthorne bridge motor control will have to use vector control method to optimize load sharing, due to the excessive system friction to overcome with limited motor power.