SUMMARY
This paper presents a case study of the methodology undertaken by QR Limited to restore Electro Motive Diesel (EMD) D29 and D31 traction motors to their original OEM builds. QR operate a fleet of CL22C and CL26C narrow gauge EMD locomotives in 80 km/h heavy haul coal, and 100 km/h long haul freight environments. Prior to the year 2000, the freight fleet operated at 80 km/h, and the coal fleet operated at 60 km/h. When the operational speeds were increased in 2000, the flashover rate of the motors increased as well. Root cause analysis of the failure modes indicated that the build of the machines could not operate with the increased power and speeds for sustained periods. The failure rate of the traction motors after the speed increases were approximately 4.5 – 5.5 failures per 100,000 km. After the rebuild program this rate decreased to about 1.

INTRODUCTION
The Freight business of QR hauls more than 59 million tonnes of minerals, agricultural and general freight each year in Queensland and Western Australia, and has a growing presence in the national rail long haul market. QR National Coal operates more than 540 coal train services per week, from 56 mines for 23 customers with an annual tonnage of approximately 185 million tonnes (08/09). The mining boom saw an increase in demand for coal haulage. To cope with these increasing tonnages, QR converted its 1550 and 2400 locomotive classes into 2300 and 2250 class locomotives. Part of this upgrade involved the addition of a turbo charger to the EMD645 2 stroke diesel engines. This increased the power output by approximately 500 extra horsepower, and placed a higher demand on the traction motors. The 2250 and 2300 class locomotives operated D31 and D29 traction motors respectively.

QR National derive locomotive hauling capacity from load tables which are based on the number of traction motors available in a consist. Because of this, motors that are cut out in service have economic consequences that can have a large impact if left unchecked. In the CL** locomotive classes, a single traction motor flashover can have the ability to cause other motors in the locomotive to flash in sympathy with it, and further de-rate the loading of the train. This paper outlines the steps taken to rebuild the EMD D29 & D31 traction motors from a machine that had a low quality build that was fit for low speed operation; into a world class build capable of operating slightly beyond the OEM requirements.

Table 1: Causes of traction motor faults prior to the year 2000

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failed main and commutating poles</td>
<td>38</td>
</tr>
<tr>
<td>Leads</td>
<td>17</td>
</tr>
<tr>
<td>Flash over</td>
<td>17</td>
</tr>
<tr>
<td>Shaft damage</td>
<td>3.5</td>
</tr>
<tr>
<td>Poled</td>
<td>3.5</td>
</tr>
<tr>
<td>Armature</td>
<td>3.5</td>
</tr>
<tr>
<td>Oil contamination</td>
<td>10</td>
</tr>
<tr>
<td>Commutator</td>
<td>7.5</td>
</tr>
</tbody>
</table>
The largest cause of motor failure at this time were due to failures of main fields, inter-poles, leads, and flash over’s. Failures from oil ingress were mainly due to engine leaks through cooling air ducting, and in the sump plates beneath the diesel engine. This oil ingress had a large contributing factor to the failures mentioned above.

2. THE COST OF FLASHOVERS

There are about 220 Clyde locomotives that operate in Freight. Prior to the year 2000 the average annual distance travelled for these locomotives was about 80,000 km. At the time the failure rate due to traction motor failures was 4.5 per 100,000 km. For an average cost of $20,000 per motor, the cost of these failures was in the range of $17M p.a. In 2008 the average annual distance travelled per locomotive rose to approximately 100,000 km, the average cost of overhauls rose to approximately $30,000 per motor and the failure rate decreased to about 1 failure per 100,000 km. Allowing for these differences, the costs of traction motor failure due to poor machine build decreased to about $8M. By simply rebuilding the motors to meet the specifications of the OEM tolerances as a minimum, and correctly shimming the commutating poles for QR service, the overhaul costs due to poor machine build decreased by about $9M.

3. FLASH OVERS

In general, a traction motor flash over occurs when the brushes that conduct the current into the armature are shorted together by ionised gas. When a flash over occurs, it consumes the energy that is stored in the main fields of all traction motors and the main alternator, generally before the ground relay has a chance to operate. The consumption of this stored energy generally results in the locomotive “jolting”. Contributors to a flash over are commutator sparking, and high speed operation of an out of round commutator. The poor quality of the machine build prior to the overhaul program created moderate levels of sparking at the brushes under heavy haul conditions. This sparking created out of round commutators. In the year 2000 when the hauling speeds were increased the original builds continued to operate at a reasonable standard while they remained in heavy haul coal traffic limited to 80 km/h. However, when these locomotives were removed from coal, and placed into 100 km/h freight operation, flash over’s occurred, generally when dynamic brake was applied.

4. DYNAMIC BRAKING

The dynamic braking of the GL22C and GL26C locomotives dissipates a continuous 200 kW of power at speeds above 27 km/h for each motor. As the speed of the locomotive increases the armature current and voltage is maintained at constant values of about 375 A and 600 V respectively, but the field current is reduced proportionally with speed to maintain the 200 kW (refer to fig (i)). As the field becomes weaker, the ratio of $I_f / I_a$ becomes smaller, leading to the air gap flux becoming excessively distorted. This flux distortion results in an uneven distribution of generated voltage across the commutator bars. Another consequence of the decreasing $I_f / I_a$ ratio is that the neutral flux zone is increased. This results in an uneven distribution of air gap flux, and creates a voltage across some of the commutator segments that becomes excessively high. When this uneven voltage distribution across the commutator is combined with brush sparking, the commutator becomes prone to flash over.

5. EFFECTS OF ROLLINGSTOCK

In the Blackwater system in Queensland, the ruling grades are Tunnel and Windah banks. Figure (ii) is a snap shot of hauling currents experienced by the D29 traction motors on one of these grades in 1999. This graph indicates that during this time period the motors were not being operated beyond their continuous rating of 450 A. Miscellaneous information on the graph includes some hunting of the diesel engine (circled). Another contributing factor to the flash over problem was brush bounce, but this only occurred in extreme cases of out of round commutators. The lower hauling speeds in coal traffic prior to the year 2000 allowed the force of the brush box spring to maintain constant contact between the commutator and the brush. Brush sparking during these hauls was moderate.

When the coal hauling speeds were increased, heavy sparking started at about 70 km/h in full notch. Some motors flashed over at these speeds and others did not.

When a high sparking level is combined with the low brush spring pressure, brush bounce, and the uneven distribution of the bar-to-bar voltage discussed earlier, ideal conditions are created to generate a flash over. Other contributing factors that created poor commutation are worn gearing, which is usually detected by small flat spots on the wheel. The number of flats is usually the same number of teeth as the bull gear. Wheel flats, wheel slip/slide conditions, and point’s crossings generate mechanical vibrations that allowed brush bounce to occur, as well as sudden shifts of the magnetic neutral axis.

The brush holder positioned under the air intake for the cooling air would occasionally become oil soaked on some locomotives. This oil leaked into the air ducting of the traction motor between strip welded steel plating, that made up the engine sump for the engine. Oil ingress had the effects of
increasing brush wear, brush sparking levels, contaminating the commutator and deteriorating the insulation system.

6. BRUSH HOLDERS

In addition to alignment tolerances, low brush spring pressure on some motors contributed to these flashovers. The movement of the brush pressure finger as it travelled toward the commutator was ½ lb lower than its outward movement. The upward travel of the spring arm was also at the lower tolerance of the OEM specifications. When the brush holder springs were assessed the issue of the OEM requirements became clouded. The OEM states a tolerance range of 4 – 5 lbs, the brush holders in use had a pressure that varied between 3 1/2 – 4 1/2 lbs. This range was measured by taking into account the...
travel of the spring arm. As the arm slowly travelled toward the commutator the tolerance was at the lower end. As it travelled slowly away from the commutator the tolerance was at the higher end. Because the outward travel of the pressure finger was at the lower end of the OEM tolerance, the spring pressure was deemed satisfactory. It became evident that the force of the pressure finger needed to fall within the OEM tolerance in both directions of travel in order for it to successfully operate in the fleet for both coal and freight.

7. COMMUTATION

Text book discussions of commutation will not be addressed in this section, however the effects that field weakening has on commutation will. The D29/D31 traction motors are a 4 pole machine. There are 201 commutator segments in the armature. When the armature voltage is 600 V the approximate voltage between each segment is 13 V (3). Fig (iii) is a chart that represents the average commutator segment voltage vs the ratio between field ampere turns per pole, and the armature ampere turns per pole for traction motors. This chart is based on traction motor research during the 1950s – 1960s (3). It represents a definitive relationship between operational stability of a dc traction motor, and the level of field weakening that it can operate successfully with. Operation above the curve represents a region of instability or poor commutation; operation below the curve represents stability or a region for good commutation for a well built motor under field weakening conditions. For an average commutator segment voltage of 13 volts, the minimum ratio of field ampere turns to armature ampere turns will be 0.62.

The D29 and D31 traction motors have main pole windings that have 29 turns. The two equations following are for the amp-turns of the field per pole, and the amp-turns per pole for the armature:

\[ \frac{MMF_{\text{field}}}{MMF_{\text{armature}}} = \frac{29 \times I_f}{2 \times 201 \times I_a} \]

\[ \frac{MMF_{\text{field}}}{MMF_{\text{armature}}} = 2.308 \times \frac{I_f}{I_a} = 0.62 \]

\[ \frac{I_f}{I_a} = 0.27 \]

The minimum acceptable field-weakening ratio is therefore 27%. Under dynamic brake conditions, as the speed increases this ratio reduces to maintain the 200 kW dissipation (refer to fig (iv)). Under full braking effort the armature current is 375 ±15 A (refer to fig (i)). At 80 km/h the ratio drops to 20%. It is evident from the above discussion that at this limit the machines are operating below the minimum acceptable field weakening ratio, making them prone to flash over and consequential damage.

Fig (iii): Commutator segment voltage : Field ampere turns/armature ampere turns
8. ORIGINAL BUILDS

Prior to the rebuild program, the overhaul of each machine was not maintained to the original OEM mechanical design tolerances. Alignment errors were introduced due to relaxed builds. These alignment errors were compounded by incorrect shimming of the commutating poles. Prior to the speed upgrades, these alignment errors could be tolerated due to the minimum field weakening ratio not being exceeded. This provided some operational leeway for the machines in the lower traffic speeds of coal (60 km/h). Once the traffic speeds were increased and the field weakening ratio began to be exceeded, the flash over problems began. These build errors were introduced by a number of mechanisms.

(a) The original motors were overhauled and refurbished motors from local contractors. In order to lower the overhaul costs, the motors were assembled with jigging that did not have the accuracy of the OEM builds, allowing alignment errors in the brush holder mounting pads in the stator frame, pole alignment, incorrect commutating pole shimming, and the alignment of the commutator with the armature core lamination stack. In some cases the misalignment between the commutator and the lamination stack was up to 3 mm.

(b) When the original motors were overhauled, the welding process to refurbish the axle DE and NDE bores introduced frame distortion. This distortion allowed the No 4 brush holder to lose its parallelism with the armature axis, as well as allowing it to become skewed with the commutator.

(c) The brush holders themselves were dimensionally inaccurate and the pressure of the spring cells was too low.

(d) The welding and machining of the pole pads sometimes introduced small hollows on the pole pad surface. This had the effect of increasing the main pole air gaps. Additionally the wheel axle bore and the armature shaft bore were in some cases not parallel which affected the meshing of the gearing.

Fig (v) represents a schematic of the stator frame with poles installed. The cut out on the r.h.s. represents where the frame mounts to the wheel axle. The dimensions represented are to ensure the correct air gap is maintained between the pole faces and the armature laminations. If the tolerances indicated in fig (v) are not adhered to and the entire pole face is not equidistant for all 4 poles, then the level of sparking at the commutator, and the operational speeds of the armature can be altered.

Fig (vi) represents the same frame with the armature installed in it. All frame machining to mount the poles and the armature in the frame need to be maintained to at least the standard of the EMD Maintenance Instructions in order to maintain parallelism between the armature shaft and the wheel shaft. All machining needs to be referenced to these axes. The displacement between the armature shaft and the wheel shaft is critical in order for correct meshing between the pinion and the bull gear to occur. The Maintenance Instruction published by EMD on the mechanical refurbishment of the frame make these tolerances clear.

9. COMPONENT ALIGNMENT

As the commutator is already mechanically ½ a commutator segment displaced between uni-polar brushes when perfectly aligned with the armature (refer to fig (vi)). Tight mechanical tolerances of the remaining components are required to ensure that these alignment errors do not compound to a state where continuous sparking occurs at the brushes. Assuming perfect alignment of the commutator to armature core. The maximum error allowable is cumulative mechanical misalignment is only about 2.5 mm. Misalignments about this value will allow circulating current to be generated, and affect brush commutation for reasons previously discussed. EMD have specified these tolerances based on this reasoning.

The commutator to armature core alignment, including commutator skew, was found to be excessive in many cases. Some of these errors were able to be rectified by a realignment process. Poor manufacturing of the commutator using uneven mica thickness often lead to unevenly spaced commutator segments over about 20% of the commutator perimeter. It was over this part of the commutator where sparking began, which eventually spread to the remainder of the commutator surface, eventually an out of round commutator resulted. Table 2 summarises the
critical tolerances that were found to be in error during the rebuild process.

10. LAP WOUND VS WAVE WOUND MACHINES

Most of the dc traction motors used in the rail industry are lap wound machines. The following brief discussion is to outline the differences with wave wound machines.

In general, for a given frame size lap wound machines produce more power than their wave wound counterparts. Wave wound machines have relatively lower overhaul costs compared to their lap wound equivalents. In addition to component alignment, a wave wound machine needs to allow for the following 4 distinct differences to be taken into consideration in order for them to perform to the same ratings as their lap wound equivalents:

(1) Lap wound machines have equalisers behind the risers of the commutator to assist with commutation; wave wound machines do not. The equalisers physically connect commutator segments that are 180 degrees apart on a 4 pole machine which allow lap wound machines to be more tolerant to component misalignment.

(2) Lap wound machines in general have an even number of commutator segments. This implies that the commutator is symmetrical with the armature; the D29s and D31s have 201 commutator segments. The brushes that are 180 degrees apart will have ½ a commutator segment difference between them (refer fig 6). Because of this difference, the set up of the brushes onto the commutator of the D29s and D31s must be to a higher precision than the Lap wound armatures for correct commutation to occur, otherwise circulating currents will be generated and cause sparking at the brushes during operation.

(3) Mechanical alignment tolerances of the interpole, main poles, and commutator – armature core lamination stack of wave wound machines are typically tighter than their lap wound equivalents.

(4) The main poles of the D29 and D31 traction motors are not concentric with the armature. The curved main pole face follows a radius larger than the armature lamination radius. This allows the wing tips of the main pole to be further from the armature than the pole centres. For the D29s and D31s this measurement is 1.4 mm (refer to “A” and “B” fig (vi)). This is to assist commutation, by forcing the magnetic flux closer to the centres of the pole face.

11. TESTING

The machines were black band tested in order to ensure poles, brush holders and armature were correctly aligned. This testing was also used to ensure that the commutating pole strengths were correct for QR operation. After the rebuild
A simple load test was developed to ensure that the builds complied with the qualifying black band testing. To determine the correct commutating pole strength, a number of motors were built with various brass shimming sizes behind the commutating poles. These ranged from 0.3 mm, 0.5 mm, 0.6 mm, 0.7 mm and 0.8 mm. These shims are stamped from brass, and their thickness is used to adjust the magnetic flux density of the commutating poles. Steel shims are also used for packing between the frame and the commutating pole shoe in order to maintain the air gaps as indicated in fig (v).

Figure (vii) shows the results for a 0.3 mm shim and figure (viii) shows the results for a shim thickness of 0.5 mm. The black band testing consisted of increasing and decreasing the interpole strengths until sparking was observed at the brushes at set armature currents in both the CW and CCW directions of rotation. The y-axis in both graphs represents the level of commutating pole current above and below the armature current. The plots represent where the brushes began to spark. An increase in commutating pole strength is a boost and a decrease is a buck. The x-axis represents the armature current. The region between the graphs in either the CW or CCW directions represents sparkless commutation, or the black band.

The testing was to determine the correct commutating pole strength to enable the motors to operate with sparkless commutation at 40 km/h and 90 km/h. A thinner shim represents stronger commutating pole strength. The trend that figures (vii) and (viii) indicate is that as the commutating pole strength becomes weaker the black band is pushed lower. This has the effect of improving commutation in the higher current/low speed regions, but affecting the lower current/higher speed operational regions. It was found that the optimal interpole strength was with a 0.7 mm shim set.

### TABLE 2: ALIGNMENT TOLERANCES OF EMD MACHINES

<table>
<thead>
<tr>
<th>Object</th>
<th>OEM Tolerances</th>
<th>Maximum Error</th>
<th>Measured Error</th>
<th>Minimum Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Holder Tolerances</td>
<td>±0.1 mm</td>
<td>±0.4 mm</td>
<td>3 kg</td>
<td>OEM</td>
</tr>
<tr>
<td>Dimensions:</td>
<td>3.6 to 4.6 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brush Holder Alignment</td>
<td>Alignment to axis = +/- 0.25mm</td>
<td></td>
<td>Alignment to axis = +/- 1.5mm</td>
<td>OEM</td>
</tr>
<tr>
<td></td>
<td>The OEM states that the mounting saddle must be parallel with the normal plane within 0.1mm and within 0.05mm of its correct position</td>
<td>Measured at brush slot centre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Pole Alignment</td>
<td>+/-0.38mm</td>
<td>+/- 2.0mm</td>
<td>OEM</td>
<td></td>
</tr>
<tr>
<td>Commutating pole Alignment</td>
<td>+/-0.38mm</td>
<td>+/- 2.0mm</td>
<td>OEM</td>
<td></td>
</tr>
<tr>
<td>Main Pole air gap</td>
<td>488.95+/-0.76mm</td>
<td>488.76+/-1.0mm</td>
<td>OEM</td>
<td></td>
</tr>
<tr>
<td>Commutating pole air gap</td>
<td>490.04+/-0.25mm</td>
<td>490.04+/-0.4mm</td>
<td>OEM</td>
<td></td>
</tr>
<tr>
<td>Commutator – armature alignment</td>
<td>± 0.03 mm averaged over 6 equidistant positions around the commutator</td>
<td>Comm - Core:  1.5 mm</td>
<td>Comm – core:  0.2 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Skew:  1.4 mm</td>
<td>Skew:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Span (50 bars): 1.2 mm</td>
<td>Span (48 bars): 0.5 mm</td>
<td></td>
</tr>
</tbody>
</table>
The D31 traction motor has an armature that has split windings. These split windings effectively lower the impedance of the motor during operation. It was found that slightly weaker commutating pole strengths were required for the D31 traction motors to achieve the same performance as the D29 motors. (refer to the two operational points of 910 rpm and 2055 rpm in fig (ix)). To achieve the same operational performance as the D29 traction motors, a 0.9 mm brass shim set was used for the commutating poles. The sole use for 2250 locomotive class that has the D31 traction motors is 80 km/h coal haulage. In order to provide better commutation at the higher currents, a 0.7 - 0.8 mm shim was used. This had the additional benefit of allowing the D31 and D29 traction motors to use the same shim set. The downside of this is that the D31s will have slightly more sparking if they are placed into freight operation.

Figure (ix) represents a summary of the operational characteristics for the D29 traction motor. The curves represent the power rating of the locomotive for each motor for notches 2 – 8. This power rating is set by the load regulator of the
locomotive; as presented these plots are simply a product of the armature voltage and current. Discussions regarding the operation of the regulator are beyond the scope of this paper and will not be addressed. Included on the graph is speed vs motor power rating plots from 40 km/h through to 100 km/h. The hatched areas represent regions of poor commutation. At 40 km/h, the field current is the same as the armature current. At 90 km/h, the field current is 42% of the armature current. The qualifying tests for the rebuilt motors after the proofing of the black band testing are represented in fig (ix) by two load points at 910 rpm and 2055 rpm. It should be noted that this graph is based on 42% field current. It was found that full field current was not required at the 450 amp test point.Sparkling would begin with 42% field current before it would at full field current. This made rearrangement of the test facility to accommodate to two different loadings unnecessary.

CONCLUSION

The improvements to the D29 and D31 motors allowed the reliability and availability for the Clyde locomotive fleet in QR to improve substantially. Provided miscellaneous failure modes such as oil leaks were controlled and maintained, the investment in new jiggings, practices and procedures, and development of a simple load test to maintain quality control showed substantial improvements. However once these measures were implemented, the only additional cost of overhaul was the load testing to ensure alignment accuracy for the components. The decrease in the flash rate also allowed substantial improvements to the operational ability of the QR Clyde fleet, by allowing higher loads to be hauled.

REFERENCES

(1) F Flinders and P. Williams, - QR Report 200409/T: Reliability Improvements to the D29 Traction Motor, 2004
(2) EMD, Traction Motor Overhaul Maintenance Instructions: 3952 series 1 to 7