BEHAVIOR AND ANALYSIS OF ROD PUMPED WELLS: COMPUTING MECHANICAL AND ELECTRICAL LOADING FOR INDUCTION MOTORS

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ABSTRACT
In this paper, the behavior and analysis of rod pumped wells are studied. In particular, the theory and practice of determining motor mechanical and electrical loading are investigated. The results from these measurements can be used to acquire further information regarding the system, including mechanical and electrical system efficiencies. The methodologies discussed in this paper are used to design rod pumping systems with correctly sized motors as well as analyze specific cases from the field.

INTRODUCTION

No matter how well designed a rod pumping system is, there will always be an associated energy cost. Typically the prime mover of a rod pumping system is either a gas powered engine or an AC electric induction motor. In this paper, we investigate the behavior of induction motors that are used as prime movers to power oil well pumping units.

Regarding an induction motor, no application in the world resembles that of an oil well pumping unit. It is the only application in which an induction motor's status can vary between being instantaneously overloaded, moderately loaded, lightly loaded, and acting as a generator, at potentially multiple times during a period of 5 seconds, or in some cases, even faster. This type of environment is completely obtuse to the environment in which an induction motor would excel. Induction motors use energy most efficiently and effectively when they are moderately to heavily loaded and operating at constant speed. The load variation that is inherent with pumping unit systems causes induction motors to vary their operating speed continuously. Coupled with the possibility of multiple starts per hour, this system will never allow optimum performance from an induction motor. In fact, there is a misconception in the industry that over sizing a motor is a way to ensure that it meets the requirements just mentioned. Oversized motors cost more up front. They will not operate as effectively nor will they use power as efficiently as a smaller, more heavily loaded motor. This results in higher operating costs. Additionally, oversized will be less affected by load variations which can cause higher peak current, higher torque on the pumping unit gearbox, higher structural loads, and higher rod string loads. These characteristics have been a topic of investigation in the literature[1,3,4,6,7,8].

Considering the above factors, it is the operator's responsibility to design an optimized pumping unit system, which includes selecting an appropriately sized motor to both start the system multiple times per day as well as drive the system. At the same time, the motor should not be materially oversized. If this is the case, then it is likely to cause inefficiency, increased component loading, and higher initial and operating costs to outweigh the motor's ability to more easily handle the system's loads. Some rules of thumb include multiplying the polished rod horsepower (PRHP) by a factor of two and using that as the motor's size requirement as well as other approximations[13]. However, with the software available today, we as operators can do better than this. Many of the predictive programs use the method that is described herein to compute a horsepower requirement for the prime mover that can result in a more optimum motor size for a given system.

In this paper, we begin by providing a basic review of electrical and mechanical loading on motors. We address the fact that motors must be analyzed from both a mechanical and electrical point of view. We explain methods to determine the mechanical and electrical loading of a motor powering a pumping unit system, taking into account both driving the system and being driven by the system. We illustrate these methods with two cases. First, we show two predictive designs which implement different pumping units to produce the same well. Second, we perform a highly detailed electrical and mechanical loading and behavioral analysis on an existing pumping unit system. The paper is concluded by outlining the major points that were addressed.

BASIC ELECTRICAL AND MECHANICAL LOADING THEORY RELATED TO MOTOR PERFORMANCE

A typical electrified oilfield is run on 3 phase, 60 Hertz, 480 V AC electricity, despite the fact that most motors have a 460 V nameplate rating. However, when in the field, the common voltage that is stated is 480 V AC, with field measurements usually in more agreement with this value than with the nominal motor nameplate value of 460 V AC. The loads in an oilfield are usually of the inductive type, primarily induction motors which are used to power artificial lift systems and pumps. When sized properly, the motors that are used for disposal wells and other such constant load applications do not use power as inefficiently as the motors that power pumping unit systems.

By design the induction motor operates most efficiently and effectively when moderately to heavily loaded and at a constant speed. This is not the case in the field. There are some considerations that need to be taken into account when sizing a motor for an oil well pumping unit. First, the motor must be sized such that it will be able to start the unit from a standstill multiple times per day, even multiple times per hour and occasionally circumstances where the system is not properly balanced. Second, from both an electrical and mechanical loading standpoint, it is important that the motor be sized to handle the varying loads that are associated with the pumping unit system, yet perform at reasonable efficiency. It is a fact that no matter how well balanced the pumping unit, nor how slow it is running, even if the polished rod load was constant throughout the stroke, the gearbox, and thus the motor, will never experience constant loading.

The induction motor is a fascinating piece of engineering. By design, it has the ability to convert electrical energy into mechanical energy for the system it is driving. It also has the ability to translate mechanical energy into electrical energy when it is being driven by the system to which it is connected. In fact, in most pumping unit installations it is common (for short durations) for the motor to be heavily loaded, even beyond its mechanical and electrical limits, as well as negatively loaded (generating), putting power back onto the grid, during the same stroke of the pumping unit. When these phenomena (i.e., overload and regeneration) occurs, the motor is both pulling current from the grid when driving the system and putting current back on the grid when being driven by the system. It is obvious that in these instances, the motor is going through considerable amounts of cyclic loading. This type of cyclic loading has been a topic of discussion in the industry for some time, especially in the context of motor sizing and analysis[2,3,4,5,9,10,11,12], and its application will be addressed in this paper.

Cyclic loading for different components of the rod pumping system is important due to its inherent impact on equipment sizing and operation, in particular the motor and gearbox. Two cyclic loading factors are currently defined and used commonly in the industry to determine loading on the motor and the gearbox. They are electrical cyclic load factor and mechanical cyclic load factor. Both are used as derating factors. In other words, they are used to make concessions for the cyclic loading and its overall effect on the component on which it is acting. As an example, consider a 30 HP motor that operates a conveyor belt at a constant load of 28 HP all day long. In this case, the motor is operating under a steady load, so the cyclic loading component is nonexistent. Now consider the same motor operating a pumping unit system with an average power output of 28 HP. It is obvious that the pumping unit will demand more than 28 HP at certain points during the stroke and less than 28 HP at other points during the stroke. This must be taken into consideration when computing the mechanical loading on the motor. The average of 28 HP in the latter case will affect the motor much differently that the former.

The variation in loading affects a motor differently in the explanation above because the effective value of a varying load over a stroke is not equivalent to applying the average load over the same period. We can think of this varying load over time as a wave form. In fact, concerning any wave form, the larger values are weighted more heavily that the smaller values when considering the effective value. Figure 1 shows the current drawn and produced by a motor connecting to a pumping unit at 10.3 SPM. This equates to a period of 5.8 seconds per stroke. Notice that the current is not steady during the stroke. This will be investigated later in this section.

The analog best used to describe this phenomenon is comparing the heating across a resistor by an alternating current versus a direct current. Consider an alternating current of i_{ac} amps, and a resistance of R ohms. We need to find the effective value of this alternating current. The effective value of the alternating current would be the amount of direct current I_{dc} needed such that when put through the same resistance of R ohms, an equivalent heating effect is produced. The heating in the resistor for the direct current is given by I_{dc}^2R. Since I_{dc} is constant, this heating is both the instantaneous heating and the average heating. The instantaneous heating in the resistor for the alternating current is given by i_{ac}^2R. In order to find the alternating current that will generate the same amount of heating through the resistance R over a given time period T (like the stroke of a pumping unit), we must determine the average heating for the alternating current over this time period. In other words, we need to satisfy

$$I_{RMS}^2 R = I_{dc}^2 R,$$

where I_{RMS}^2 is the effective value of the alternating current over the time period T. With respect to the direct current example, the average heating over the given time period T is $I_{dc}^2 R$, since the current and the resistance are constant. However, with respect to the alternating current, the average heating over the given time period T is

$$\text{Average Heat} = I_{RMS}^2 R = \frac{1}{T}\int_0^T i_{ac}^2 R\, dt.$$

Solving the above for above for I_{RMS} we find the effective alternating current to be given by

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i_{ac}^2\, dt}.$$

The effective current of I_{RMS} will cause the same amount of heating as I_{dc}through a given resistance. The formula used for the effective current is exactly the definition of the root mean square current, which will be introduced next.

The root mean square (RMS) value of a set of values (or a continuous-time waveform) is the square root of the arithmetic mean (average) of the squares of the original values (or the square of the function that defines the continuous waveform). This value is the value that is measured by a multi-meter that exhibits the phrase *True RMS*— it measures the instantaneous effective values of the current at that point in time.

Fluctuation of these instantaneous RMS currents is always exhibited by every electrified pumping unit system. A multi-meter simply cannot display or keep track of these fluctuations. It does not have the functionality to correctly compute the effective heating value of the current on a per stroke basis for a motor operating a pumping unit, which is the most effective method to determine motor loading. It is not the tool that should be used to determine the electrical loading of a motor under a varying load. Special dynamometer equipment is necessary to record these fluctuations at a sufficiently high sampling rate in order to calculate the RMS current over a stroke and produce a plot of the current versus time or versus the polished rod position.

We can glean some interesting characteristics of motor behavior by inspecting Figure 1. Notice that the maximum current measured over the stroke is 55.6 amps, but the effective value or RMS current is 29.1 amps. This means that the motor is heating to a point that is equivalent to driving a constant load which would cause the current drawn to be 29.1 amps. By measuring the RMS current over a stroke of the pumping unit, one can obtain the electrical loading of the motor that is powering the pumping unit. It is this value that should be compared to the motor's nameplate full load current to determine whether or not the motor is overloaded electrically. Also observe that the current is never negative. In fact, the minimum value of the current is approximately 15.7 amps and it occurs three times during the stroke. The small peak between 2 and 3.5 seconds is current that is being produced by the motor. During this time, the pumping unit is driving the motor as a generator.

Regarding the usual average current I_{AVG}, which in Figure 1 is 26.5 amps, it is always the case that it is less than or equal to the RMS current, with equality occurring only when the load is constant. This means the heating that occurs in a motor driving a constant load is less than the heating that occurs when a motor is driving a varying load with the same average current draw. It turns out when the average current draw stays the same but the variation in current increases, the heating effect on the motor also increases. This characteristic of motor loading requires the use of a derating factor which takes into account the degree of variation in loading and adjusts the effective loading on the motor appropriately.

Up to this point, we have discussed the effective (RMS) value I_{RMS} and the average value I_{AVG} of current over a stroke. The average current will always be less than the RMS current with respect to motors powering pumping units. We are now in a position to define the electrical cyclic load factor. The Electrical Cyclic Load Factor (ECLF) is defined to be

$$\text{Electrical Cyclic Load Factor} = \frac{I_{RMS}}{I_{AVG}}.$$

The ECLF is a measure of the evenness of the current drawn by the motor. The best the ECLF can ever be is 1, which implies no cyclic loading. The ECLF of the system measured in Figure 1 is 1.098. In general, the Cyclic Load Factor (CLF) of a set of data is defined to be the quotient of the RMS value of the data and the mean value of the data. The notion of a CLF will also be used below when discussing mechanical motor loading.

A second implementation of the RMS calculation can be used to infer the mechanical loading on the motor. Since there is no way to easily measure the true output torque (or power) on the motor, the relationship between the mechanical (gearbox) cyclic load factor, polished rod horse power, and motor shaft output horsepower are used. For most cases, this method is accurate enough. However, the results will be on the conservative side. For a more accurate analysis, one would have to include the system's rotary and articulating inertia to better approximate output power required by the motor.

As discussed above, it is not uncommon for the motor to have periods during each stroke where it is driven by the system; at those same instances, torque is being applied to the opposite side of the gear teeth in the gearbox, thus creating what the industry has defined to be negative gearbox torque. Because of the fluctuations in torque on the gearbox, similar to the prime mover, the gearbox also undergoes cyclic loading during the stroke of a pumping unit. Thus, it makes sense that the procedure for finding the mechanical output power required by the motor utilizes the cyclic load factor for gearbox torque.

Obviously, the instantaneous horsepower requirements at the polished rod can vary tremendously during the stroke of the unit. Thus, we compute an average horsepower at the polished rod during the stroke. Each time a load and position point is measured at the polished rod, a torque measurement on the gearbox is computed. Using the definition of the CLF stated above, we take the average value of the gearbox torques calculated during the stroke and calculate the corresponding mechanical cyclic load factor (MCLF). The MCLF is analogous to the ECLF, except that instantaneous currents are replaced by instantaneous torques calculated during the stroke. The estimated surface drive train efficiency, which is the efficiency from the output shaft of the motor to the polished rod, is usually in the range of 70-90%. After computing the average polished rod HP and multiplying by the MCLF, we obtain the RMS polished rod horsepower. Dividing the RMS polished rod horsepower by the surface drive train efficiency, we obtain an estimated value for horsepower required at the output shaft of the motor during the stroke of a pumping unit.

PREDICTING MOTOR LOADING ON A PUMPING UNIT

There exist predictive programs with electrical analysis abilities. We illustrate the effects of different designs on a motor's electrical and mechanical loading. In both cases we consider an 8,000 ft. well with 2.875" tubing anchored at the pump. The two pumping units considered are an M320-256-100 running CCW and a C320-256-100 running CW, both at 10 SPM with a fiberglass-steel composite rod string and a 1.5" pump. The prime mover for both units is a 30 HP, 39 Amp, NEMA D induction motor. The point of this analysis is not to determine a superior pumping unit, but to show how different designs can affect a rod pumping system's performance, power consumption, and efficiency.

The layout of the graphs in Figure 3 is such that the conventional system is in the left hand column and the Mark II system is in the right hand column. Notice that the design for this well produces a surface dynagraph with an up and to the right tendency (under travel). This usually implies a pump stroke that is shorter that the surface stroke of the pumping unit. It is obvious from inspecting the dynagraph cards and their respective permissible load curves in Figure 3 that the conventional system seems to fit better. In other words, the surface card has the same tendency as the permissible load curves in the conventional system, but opposite tendencies in the Mark II system. This results in a lower (and more desirable) MCLF of 1.204 in the conventional case, which in turn most often computes a lower required output power at the motor shaft, as is the result here. The Mark II mechanical cyclic load factor is 1.494. Due to their respective MCLFs, the conventional system requires 24.99 HP at the motor shaft, while the Mark II system requires 30.67 HP. Table 1 lists these and other values from this analysis. Observe that the predictive system estimated that the surface drive train efficiency was higher with the Mark II. In this case, the difference in surface drive train efficiency did not outweigh the difference in cyclic load factors when computing the power required.

Using Figure 3, the interested reader can further analyze the relationship between the dynagraph, gearbox torque, motor current, and motor power by drawing a vertical line through the position of interest during the stroke of the pumping unit. For example, regarding the Mark II case, one could sketch a vertical line through approximately 84" into the upstroke and note that this is where the surface card is closest to the permissible load curve during the upstroke. If the reader moves down again to the torque versus polished rod position graph, this where the peak torque occurs on the gearbox. Moving down to the current versus polished rod position graph, 84" into the upstroke is the point just before the current reaches its peak.

There are some interesting facets of sucker rod pumping. First, increasing (decreasing) current typically lags increasing (decreasing) gearbox torque with respect to polished rod position. In other words, peak gearbox torque is attained before peak current. See Figure 3. All the rotating parts, especially the crank arms and counterweights have a high amount of inertia—even the sheaves, due to their high rotation speed. Because of this there is a rundown effect between the motor and the slow speed shaft. The length of this rundown is dependent upon the amount of speed variation of the motor and the amount of rotary inertia between the gearbox and the motor shaft. Second, the motor RPM lags gearbox torque. See Figure 3. Similarly, motor RPM lags current. These relationships will be investigated further in the diagnostic case study.

The information from the predictive analysis can prove useful in determining the optimum size motor to both start the pumping unit system as well as power the system while handling the cyclic loading during the stroke. With respect to starting a pumping unit system from a standstill, the most effective motor is the NEMA D. Design D motors have a starting torque of approximately 275-300% of full load torque. This is much higher than the 150-175% of NEMA B motors. Nema D motors are built with more rotor resistance which creates the following characteristics for a motor. First, it causes the motor's peak output torque to occur at or very near the locked rotor (which is when the motor first begins to rotate). Second, it causes the motors to be slightly less efficient than NEMA B motors. However, due to this increased resistance in the rotor, the NEMA D has a higher slip, typically 5-8%, which in turn allows more motor speed variation. This is beneficial for two reasons. First it allows more inertia benefit from the rotating components of the pumping unit system. This reduces loading on the gearbox, structure, and rods. Second, NEMA D motors tend to have lower peak currents due to the higher variation in speed. This is an effect directly related to the decreased amount of torque required to drive the rod string. Not only does this lower gearbox loading and decrease the CLFs, it causes the required power at the motor to be less than it would be with a lower slip motor, like the NEMA B. It also typically reduces rod loads since the peak load is usually reduced and minimum load is usually increased. This implies a lower peak rod load coupled with a lower stress range on the sucker rod string, thus translating into lower rod string stress loading.

In order to implement a NEMA B with comparable starting torque, usually a size up from the required NEMA D motor must be selected. Motors operate most effectively and efficiently when they are moderately to heavily loaded and operating at a constant load. These two requirements can be obtained by sizing the motor correctly (not over sizing) and by minimizing the MCLF, which in turn reduces the amount of cyclic loading on the motor. Even though the NEMA B is a more efficient and less expensive motor when compared to a NEMA D of the same HP rating, it is most probably the case that both advantages just mentioned are lost when the NEMA B is upsized so that the required starting torque can be realized. More research with reliable data needs to be done in this area.

Regarding the power required in order to drive a given rod string, pump, and fluid load, the parameters that impact the mechanical loading are the polished rod horsepower, the MCLF, and the surface drive train efficiency. Out of these three parameters the one with the most influence on mechanical motor loading and the horsepower required from the prime mover is the MCLF. The reciprocal of the MCLF can be considered as a derating factor for the motor. Its use allows the operator to compute the effective horsepower of the motor given its rated horsepower. Likewise, we can use the MCLF as a multiplier to increase the average load on the motor to the effective load. This process computes the corresponding steady state load that would load the motor just as it is loaded with the varying loads over the stroke. Of course, the surface drive train efficiency is included in both calculations.

DIAGNOSTIC CASE STUDY

Consider a well with the seating nipple at 7150 ft and a composite fiberglass-steel rod string with 1.5" sinkerbars. The pumping unit is a C228-246-86 running counterclockwise at 10.1 SPM. This means that each stroke lasts 5.94 seconds. The prime mover is a NEMA D 6 pole 60 Hertz 460V AC induction motor. The rated power is 25 HP at 1135 RPM. The slip is 5.42%. The current draw at full load is 31.5 amps. The unit is weight heavy, with a maximum gearbox torque of 225,232 in-lbs occurring at 61.8" from the bottom of the stroke during the downstroke and 157,856 in-lbs occurring 33.6" into the upstroke. The gearbox is loaded to 98.8%. The MCLF is calculated to be 1.54. See Figure 4. Gearbox torque without the consideration of inertia is 234,032 in-lbs and overloads it at 102.6% of its rating. See Figure 5. The speed variation is approximately 15.12%, with instantaneous maximum and minimum motor RPMs of 1230 and 1044, respectively. Figures 4, 5, and 6 show a plot of motor RPM versus polished rod position.

The current plot in Figure 6 also indicates a weight heavy condition, with maximum upstroke and downstroke currents of 35.0 amps and 52.4 amps, respectively. Notice however that the motor is not electrically overloaded in this case since the RMS current is 30.1 amps. The motor is loaded to 95.6% of its electrical rating on this stroke. The average current is 27.5 amps, and thus the ECLF is 1.095. See Figure 6. Notice in Figures 4, 5, 6, and 7 that the motor is the last to feel the effects of speed variation. When system torques and RPMs change, the motor current reaction lags these changes.

Using the fact that the average polished rod power over the stroke is 12.6 HP, the MCLF is 1.54, and the estimated surface drive train efficiency is 89.9%, the required mechanical power at the motor shaft is approximately 21.6 HP. This loads the motor mechanically to 86.3%. Notice that the electrical loading is different than the mechanical loading. This illustrates an important fact that motor loading needs to be analyzed from both a mechanical and electrical point of view. It should also be noted that if we simply doubled the PRHP, the recommended motor size would have been 30 HP.

The surface dynagraph card also gives a qualitative view of the loading on the gearbox considering the effects of inertia. Notice in Figure 8 that the surface card seems to almost touch the lower permissible load curve during the downstroke. Actually, the closest it comes to the permissible load curve is at a polished rod position of about 61.8". This corresponds to the peak torque depicted in Figure 4. In Figure 9, the permissible load curves are plotted without the consideration of inertia. In this case, the surface dynagraph card actually crosses the curve at about 67.3" and remains overloaded until 61.8". This corresponds to the peak torque depicted in Figure 5.

Finally, by plotting the motor RPM and the total rotary and articulating inertia torque in the system versus time in Figure 10, one can see the relationship between speed variation and the amount of inertia torque generated as well as its reduction in peak torque on the gearbox. Additionally, by inspecting Figure 10, it is evident that during just one stroke of a pumping unit, the motor experiences a wide variety of loading. For the first 0.54 seconds of the upstroke, the motor is driving the load and is not overloaded. From 0.54 seconds to 1.65 seconds, the motor is still driving the system, but it is now overloaded, since the RPM is lower than its rated full load RPM of 1135. The motor actually reaches its peak loading during the upstroke at about 1.23 seconds at a speed of 1105 RPM. After this point, it begins to accelerate. From 1.65 seconds to 2.10 seconds, it is driving the load and it is not overloaded. At about 2.10 seconds into the stroke, some interesting events happen. At this instant the motor crosses over into a generating mode, since the pumping unit is now driving the motor. At about 2.55 seconds, the motor reaches its maximum instantaneous speed of 1230 RPM. The motor begins to decelerate at this point. At about 2.85 seconds, the unit reaches the top of the stroke and continues to drive the motor into the beginning of the downstroke until about 2.94 seconds. At 2.94 seconds, the motor begins to drive the system again. At this point it begins drawing current instead of putting it back on the grid as it was doing during the generating mode it just experienced. From this point until 3.33 seconds, the motor is driving the load, decelerating, increasing its current draw, but it is not overloaded. At 3.33 seconds, the motor continues to decelerate and drive the load, but it is now running below 1135 RPM. It has again become overloaded at this point during the downstroke. It continues to drive the system and reaches its maximum overloaded state at 4.14 seconds at an instantaneous speed of 1044 RPM. After this point, the motor begins to accelerate while driving the load and eventually ceases to be overloaded at about 5.07 seconds into the stroke. It continues to drive the load in a non-overloaded condition until it reaches the end of the downstroke at 5.94 seconds.

One should also observe the relationship between inertia torque on the system and the acceleration and deceleration of the motor. Notice that the motor is decelerating for the first 1.23 seconds of the stroke. During this time period, the counterweights are dissipating stored energy because they want to keep moving at the same rate. During this interval, they are relieving some stress on the gearbox. That is why the inertia torque for this interval is negative. At 1.23 seconds, which is virtually the same instant that the motor is neither decelerating nor accelerating, the inertia torque is zero. From 1.23 seconds until about 2.55 seconds, the motor is accelerating the crank arms and counterweights, storing potential energy. The cranks, weights, and other components resist this acceleration and actually add to the torque on the gearbox. That is why the inertia torque is positive during this time period. A similar deceleration effect occurs from 2.55 seconds through 4.14 seconds. The weights again dissipate their stored energy, trying to maintain their rotation speed as the motor slows down to drive the increasing load. This again removes some torque from the gearbox. Thus, the inertia torque is negative for this interval. Finally from 4.14 seconds through 5.64 seconds, the motor is accelerating and the inertia adds to the gearbox load. From 5.64 seconds to the end of the stroke at 5.94 seconds, the unit is again decelerating, and the inertia torque once again works in favor of reducing the torque on the gearbox.

CONCLUSION

The premise of this paper was to provide an explanation of the behavior of rod pumped wells with particular attention paid to analyzing the mechanical and electrical loading for induction motors. Since the components of a rod pumping system are all interdependent, analysis of the other surface components was addressed as well. An attempt was made to illustrate the complexity of a seemly simple machine.

In order to understand rod pumping systems more fully, a basic understanding of the components is a necessity. This paper began by explaining the environment that best fits the application of an induction motor, and how the rod pumping system is the furthest thing from this. Many motor manufacturers still do not have a firm grasp on how the rod pumping system affects their motors and vice versa. The idea that the motor can go from driving to generating in a five second period surprises many in the induction motor industry.

The ideas of cyclic loading and its effects on motor performance were introduced. Methods to compute electrical and mechanical loading on the motor were provided, along with examples for illustration purposes. These ideas can be implemented from a design and analysis standpoint to better optimize existing rod pumping systems. This includes optimum motor sizing and appropriate methods to calculate the mechanical and electrical loading of a motor under a varying load.

ACKNOWLEDGMENTS

The authors would like to thank the management at Pioneer Natural Resources USA, Inc. for their permission and support for writing this paper. The authors would also like to thank Ken Nolen for his valuable insight concerning the topics of this paper.

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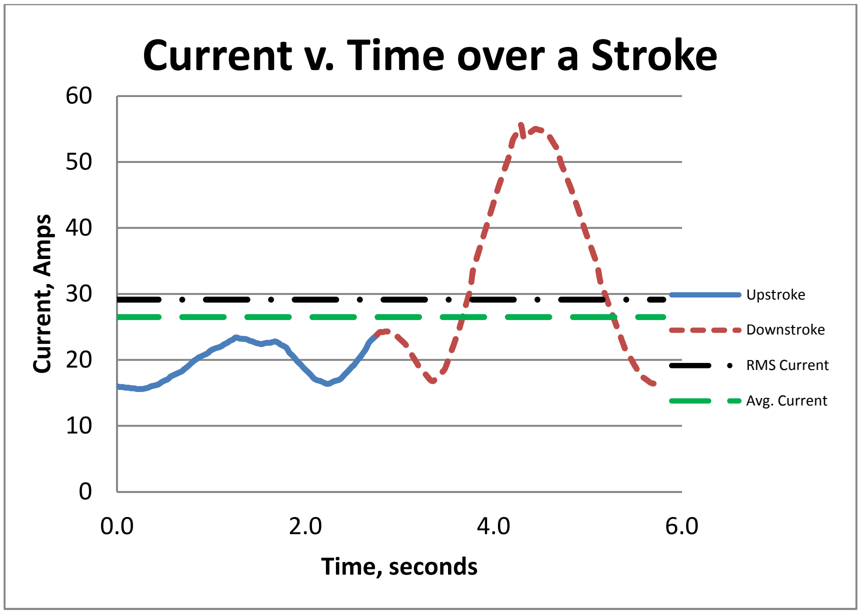

Figure 1 - Measured Current Over the Stroke of a Pumping Unit

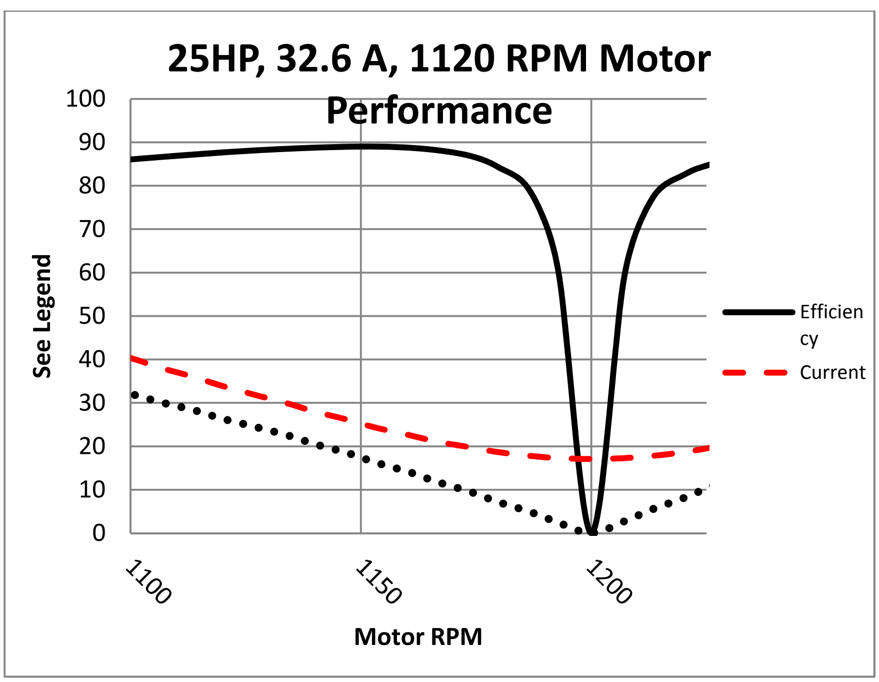

Figure 2 - Motor Performance Curves

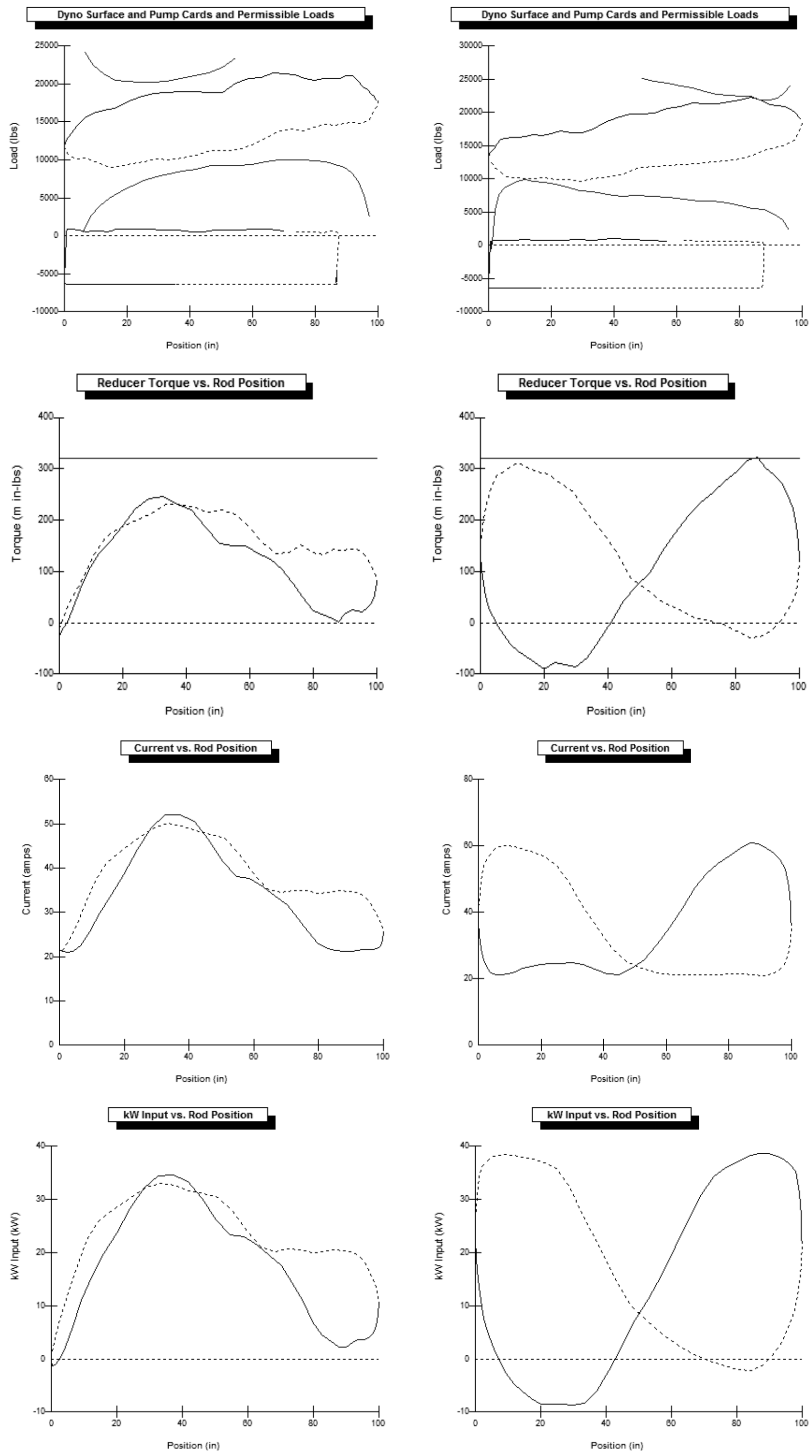

Figure 3 - Comparison of Different System Designs Associated and System Parameters

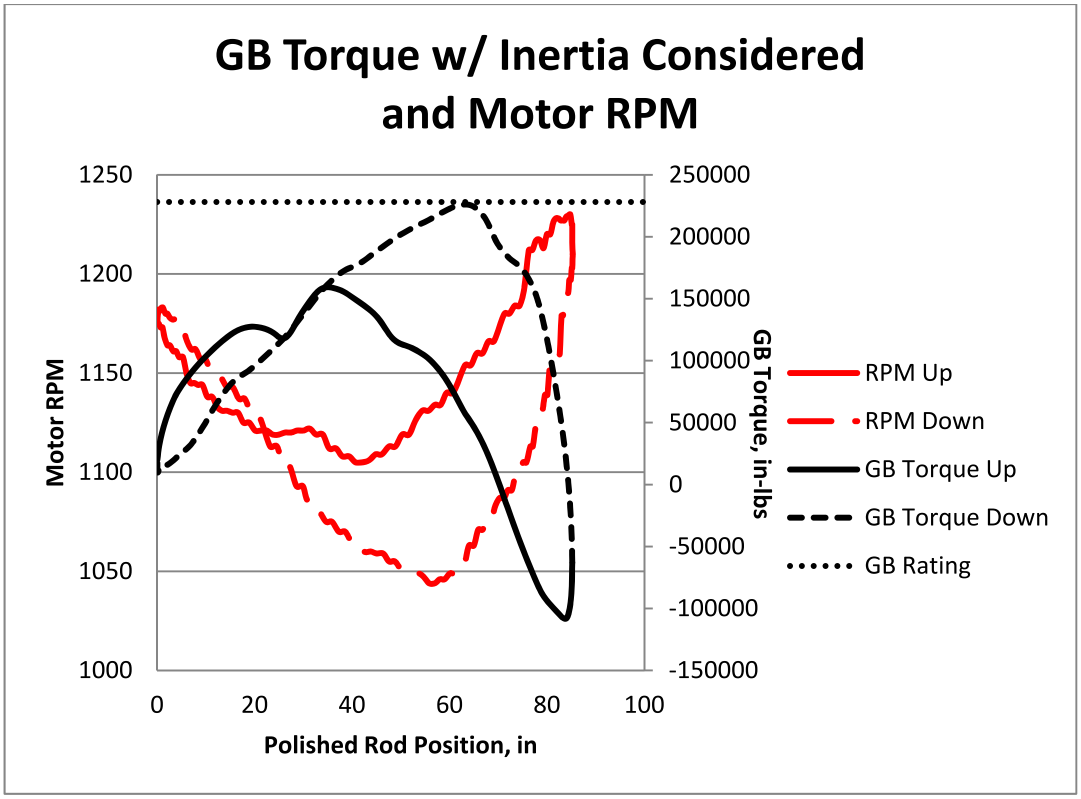

Figure 4 - Gearbox Torque Considering Inertia and Motor RPM V. Polished Rod Position

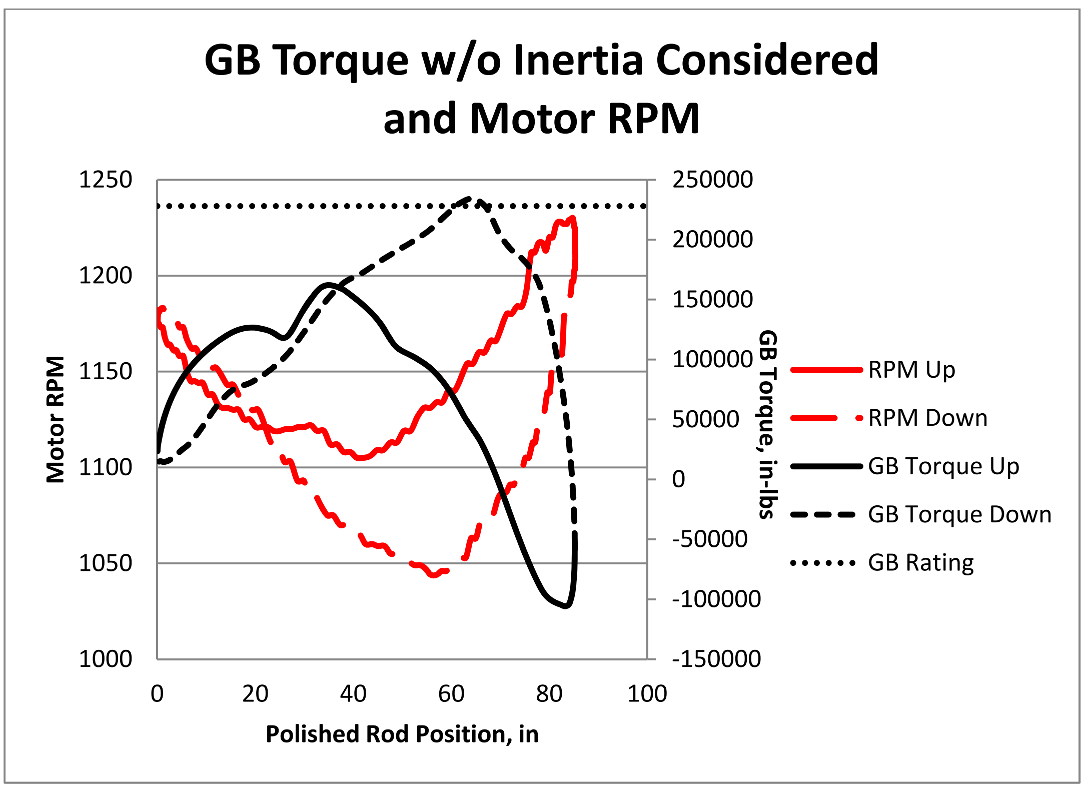

Figure 5 - Gearbox Torque Without Considering Inertia and Motor RPM v. Polished Rod Position

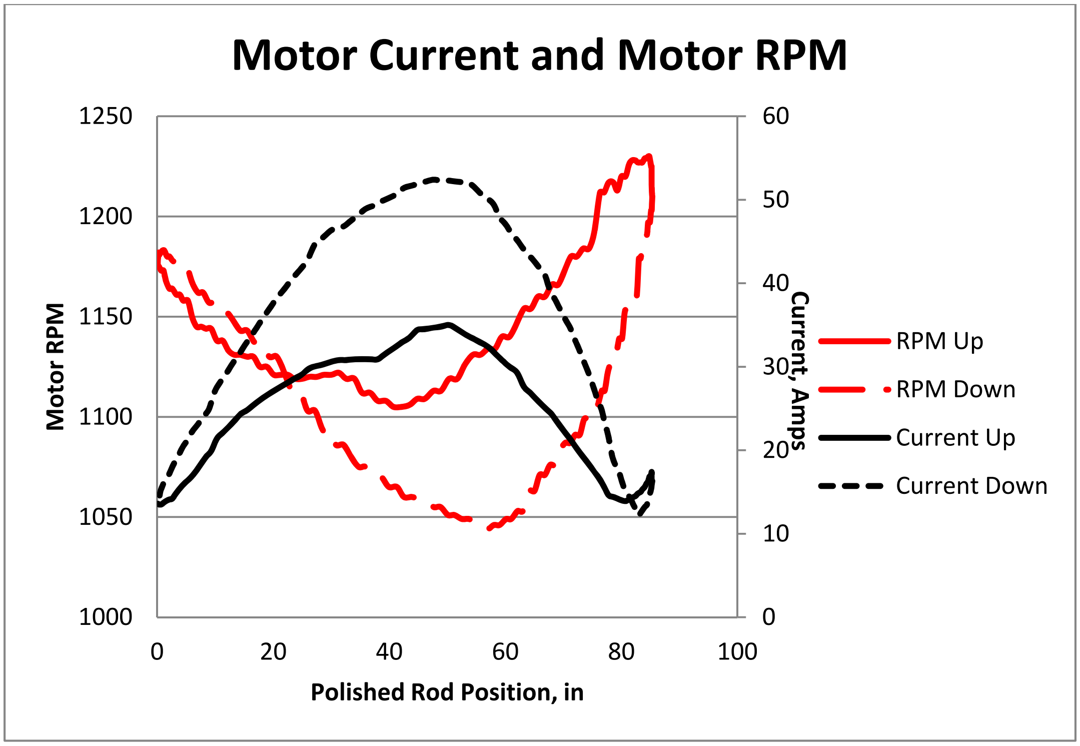

Figure 6 - Motor Current and Motor RPM v. Polished Rod Position

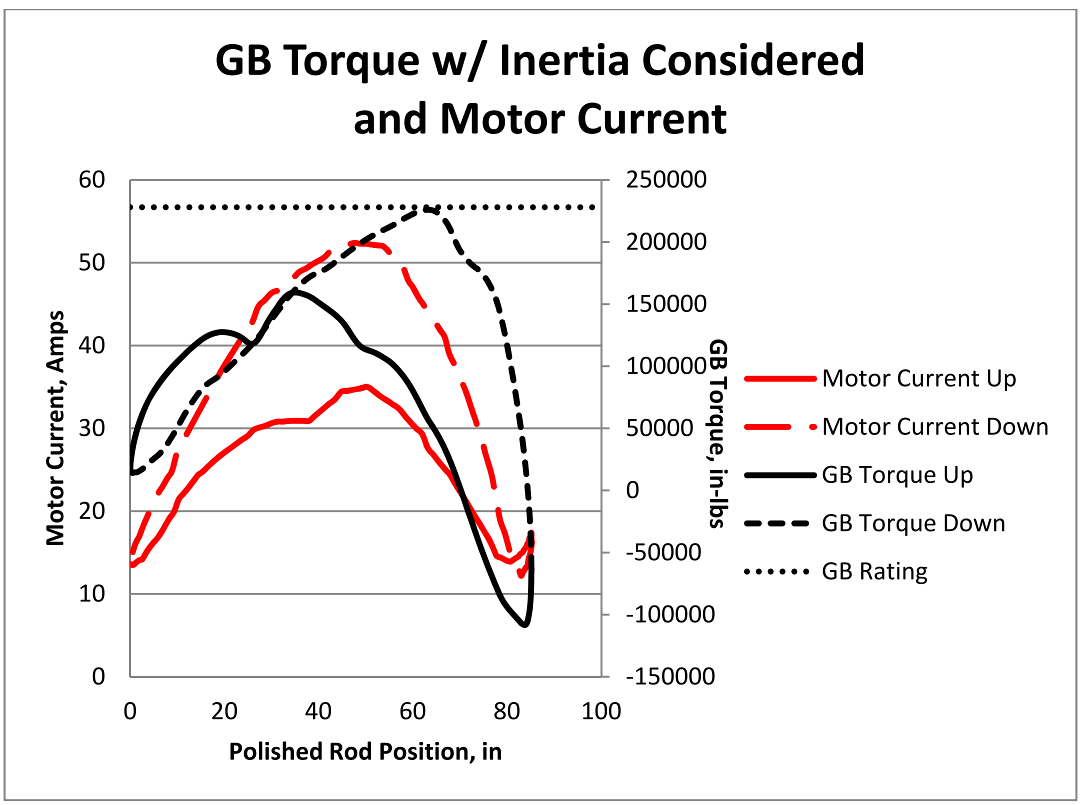

Figure 7 - Gearbox Torque Considering Inertia and Motor Current v. Polished Rod Position

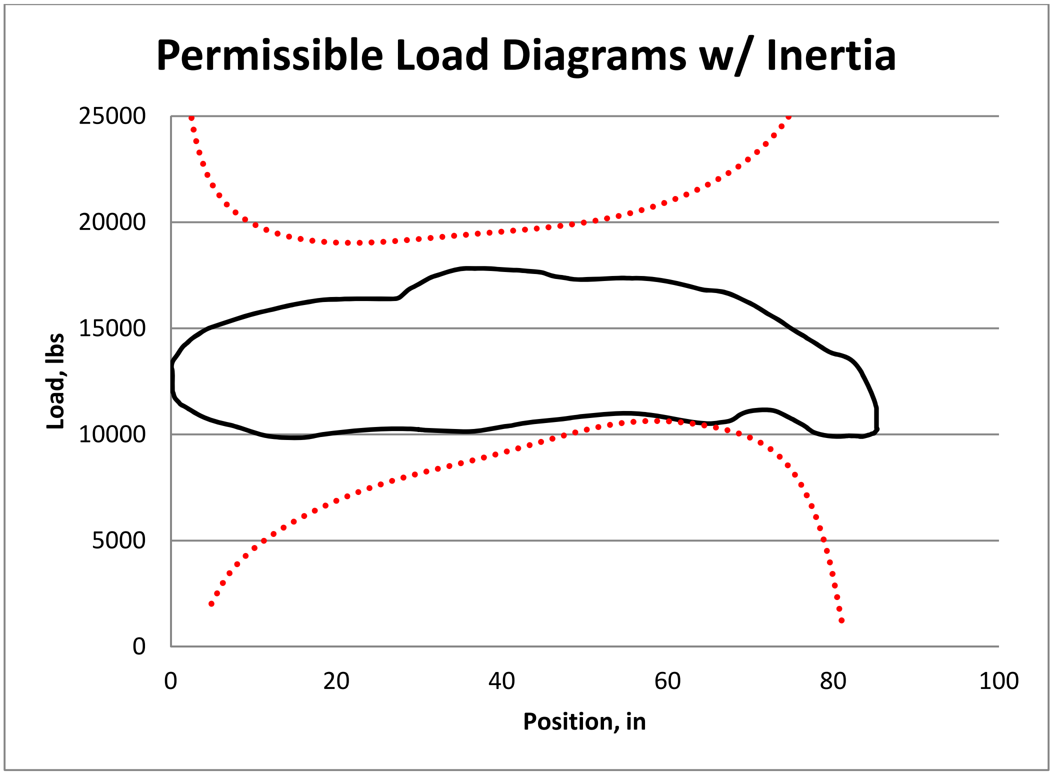

Figure 8 - Dynagraph Cards with Inertia Considered

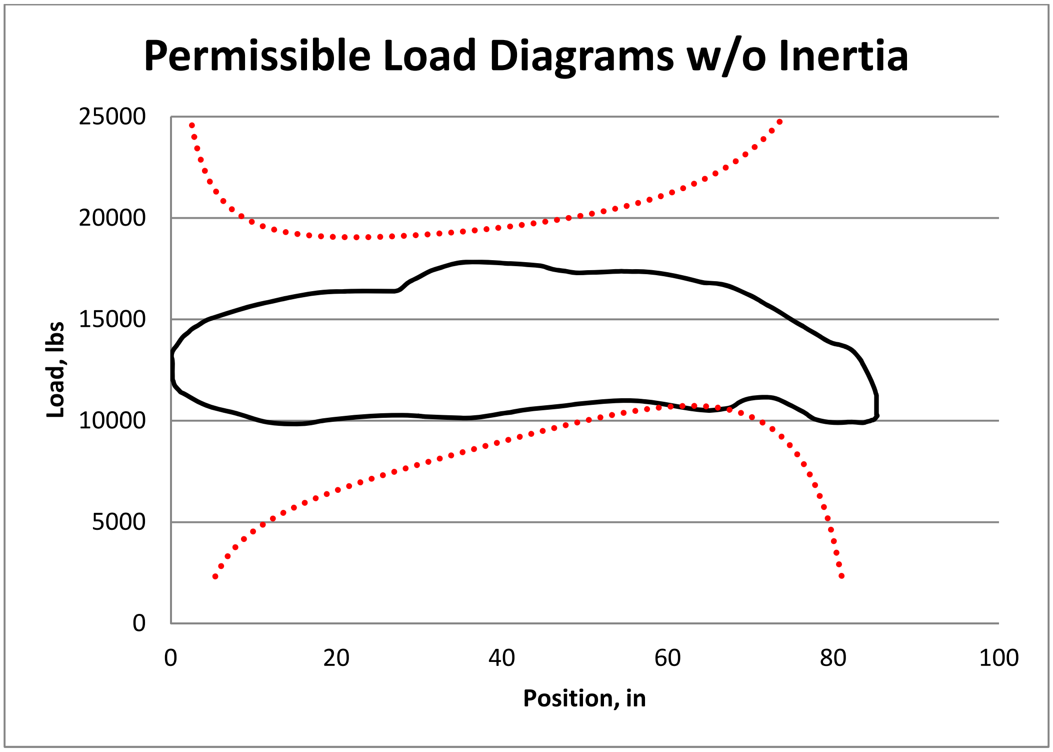

Figure 9 - Dynagraph Cards Not Considering Inertia

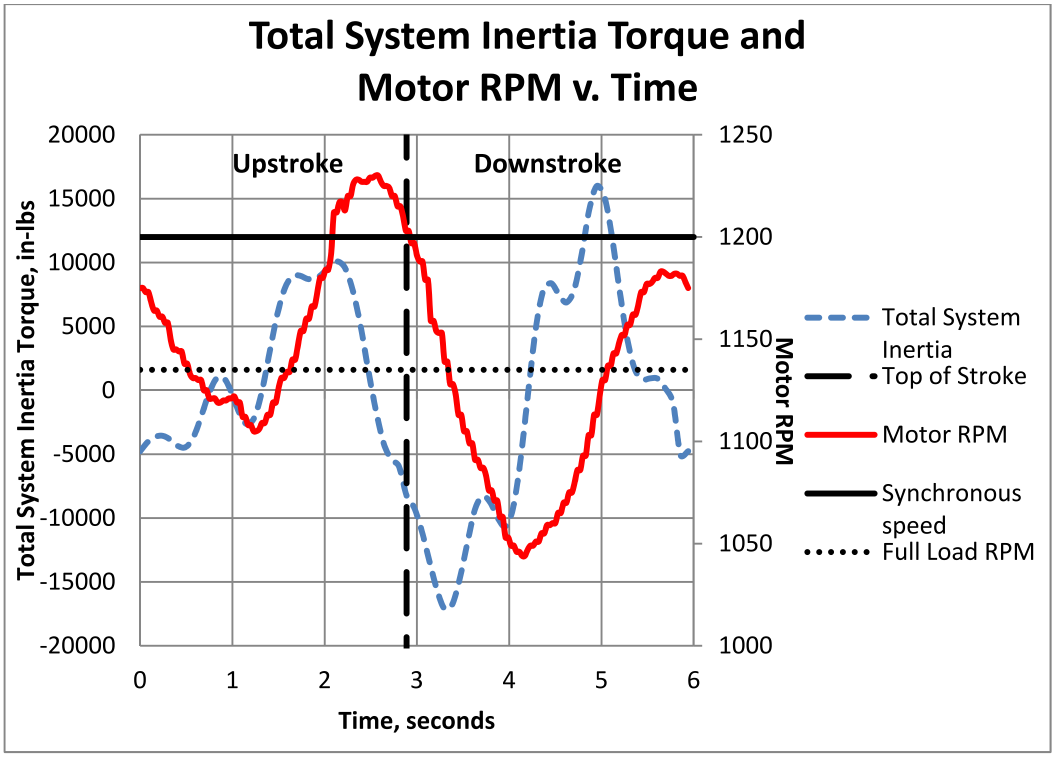

Figure 10 - Total System Inertia Torque v. Motor RPM.

Table 1
Comparison of the effect of different designs on
system performance, power consumption, and efficiency.

Pumping Unit	M320-256-100	C320-256-100
Motor	30 HP, 39 Amp	30 HP, 39 Amp
Power Required (hp)	30.67	24.99
Motor Load (% of Rating)	102.2	83.3
Input HP to Motor Detent (kW)	25.25	23.54
Input HP to Motor Non-Detent (kW)	23.90	23.47
Regenerative Power (kW)	1.35	0.07
Average Power Output (hp)	20.53	20.32
Average Power Factor	0.658	0.682
Demand (kW)	17.8	17.5
Drive Train Efficiency %	90.0	88.1
Overall Efficiency %	58.1	59.8
Motor Electrical Loading (% of Rating)	106.7	91.2
Surface Max Load (lbs)	22356	21565
Surface Min Load (lbs)	9583	8944
Average Pumping Speed (SPM)	9.92	9.94
Speed Variation (%)	18.4	12.4
Cyclic Load Factor for Torque	1.494	1.204
Structure Load (% of Rating)	87.3	84.2
Polished Rod Horse Power (hp)	18.48	18.29
Computed Surface Stroke (in)	100	100.7
Existing Max Torque (m in-lbs)	322.3	252.5
Existing Min Torque (m in-lbs)	-90.2	-23.8
Existing Gearbox Load (% of Rating)	100.7	78.9
In-balance Max Torque (m in-lbs)	315.5	247
In-balance Min Torque (m in-lbs)	-91.5	-24.2
In-balance Gearbox Load (% of Rating)	98.6	77.2